Optical Fibres

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Module: Fibre Optic Communications

MSc/MEng – Digital Communication Systems

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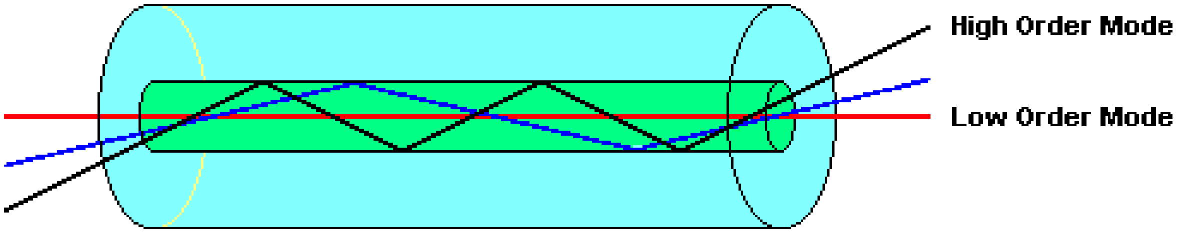
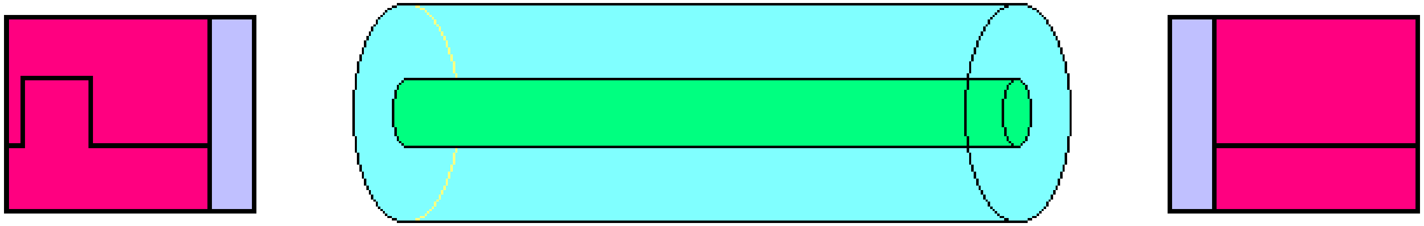
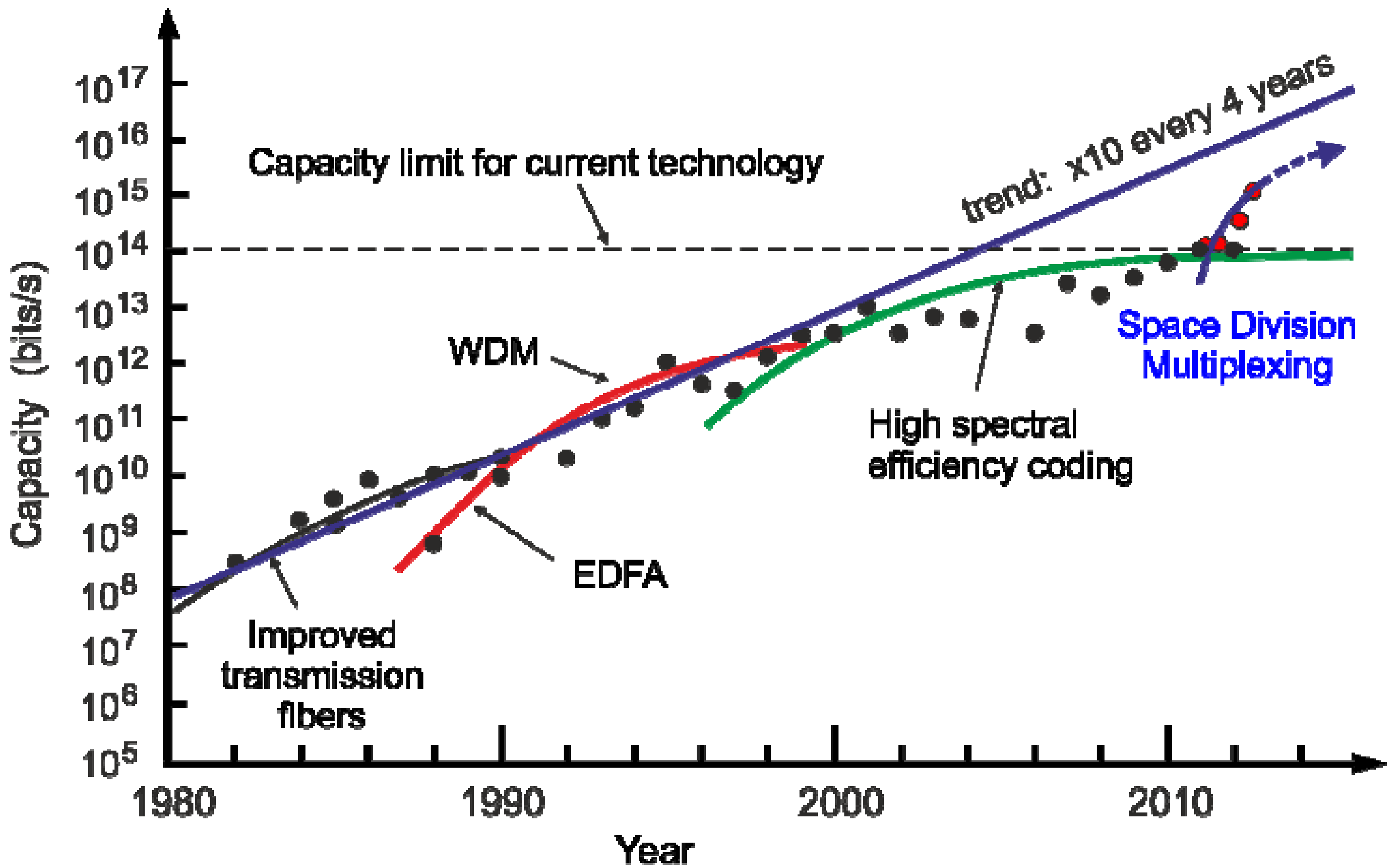
Problems to be avoided





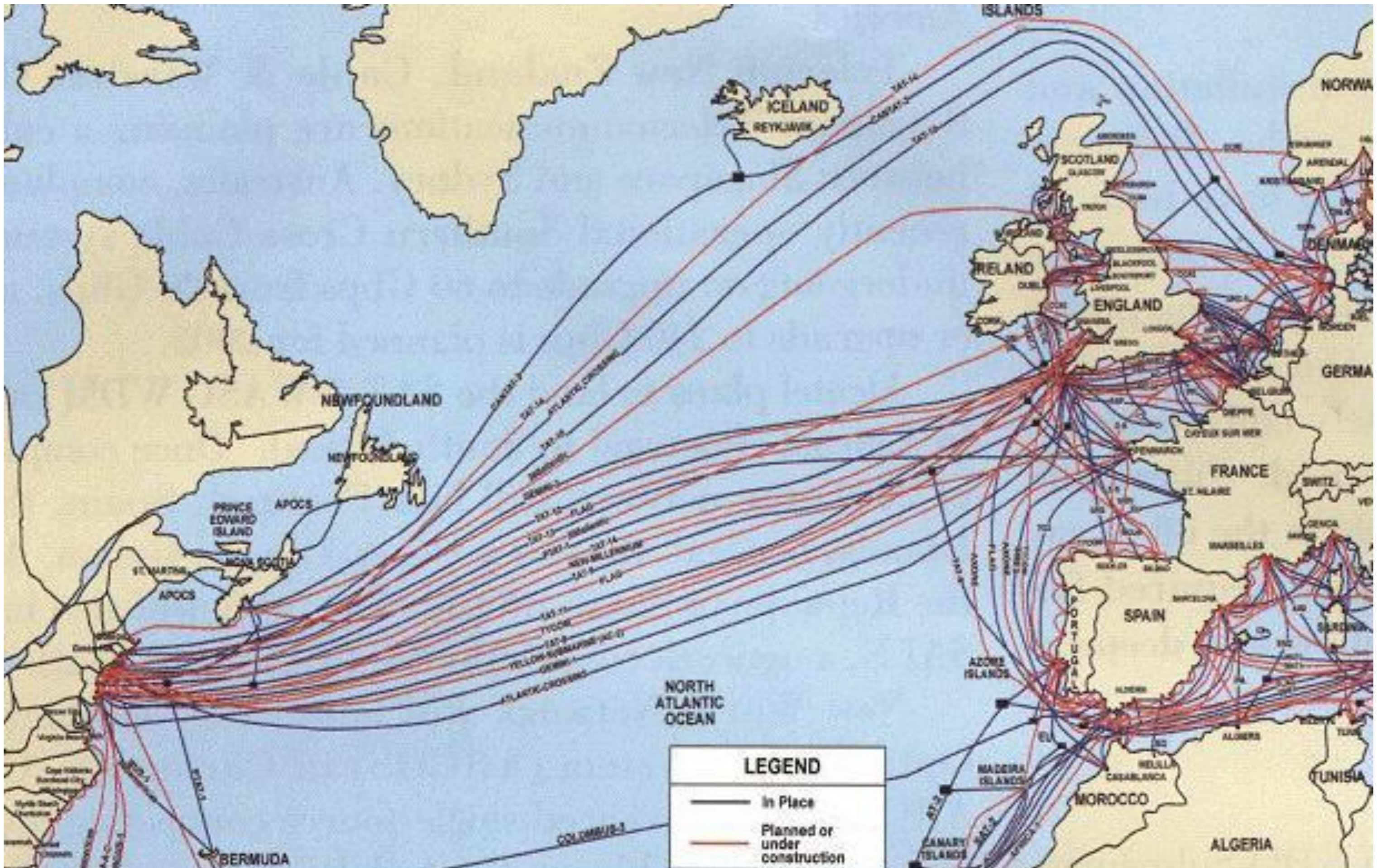
The evolution of transmission capacity in optical fibres



Key previous technological breakthroughs include

- The development of low-loss single-mode fibres,
- The Erbium Doped Fibre Amplifier (EDFA),
- Wavelength Division Multiplexing (WDM) and more recently high-spectral efficiency coding via DSP-enabled coherent transmission.
- Space Division Multiplexing (SDM) appears poised to provide the next step change in transmission capacity.

TransAtlantic Fibre Optic Cables

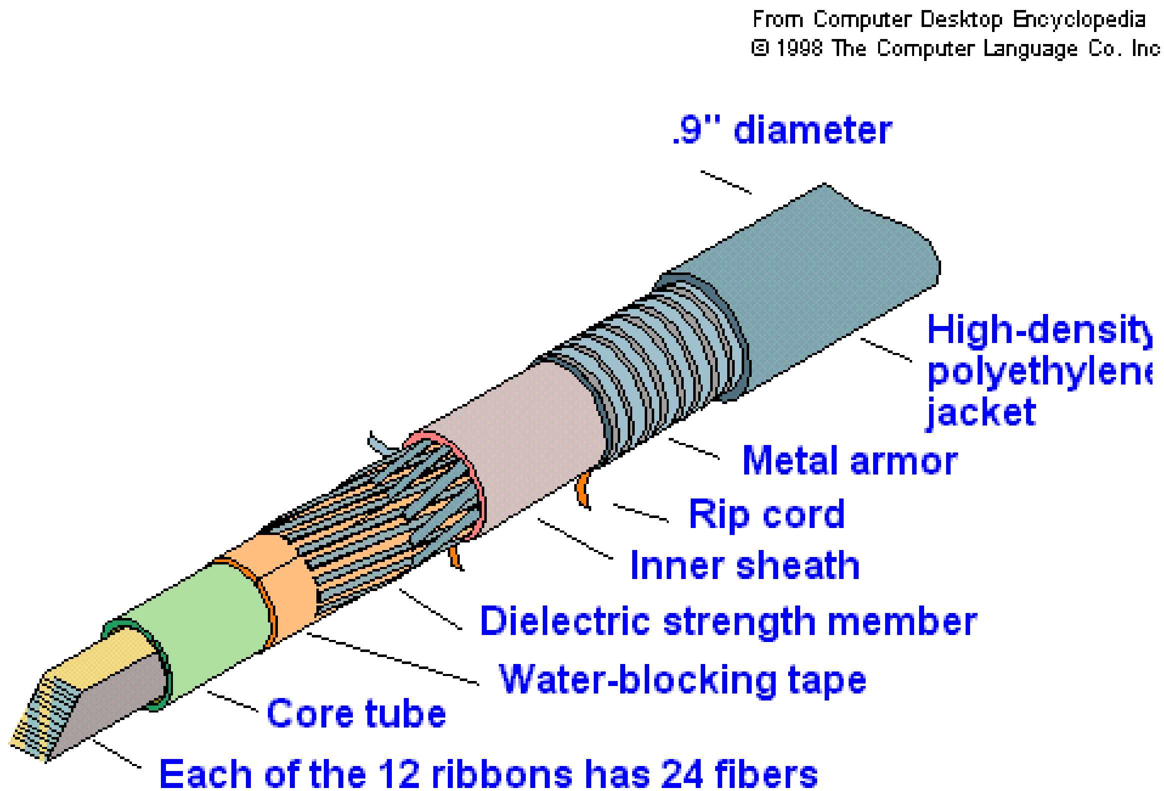


$80,000,000 Cable Landing Station in Halifax Completed

Feeding fibre optic cable into a cable ship storage tank, getting ready to lay the cable on the bottom of the ocean.

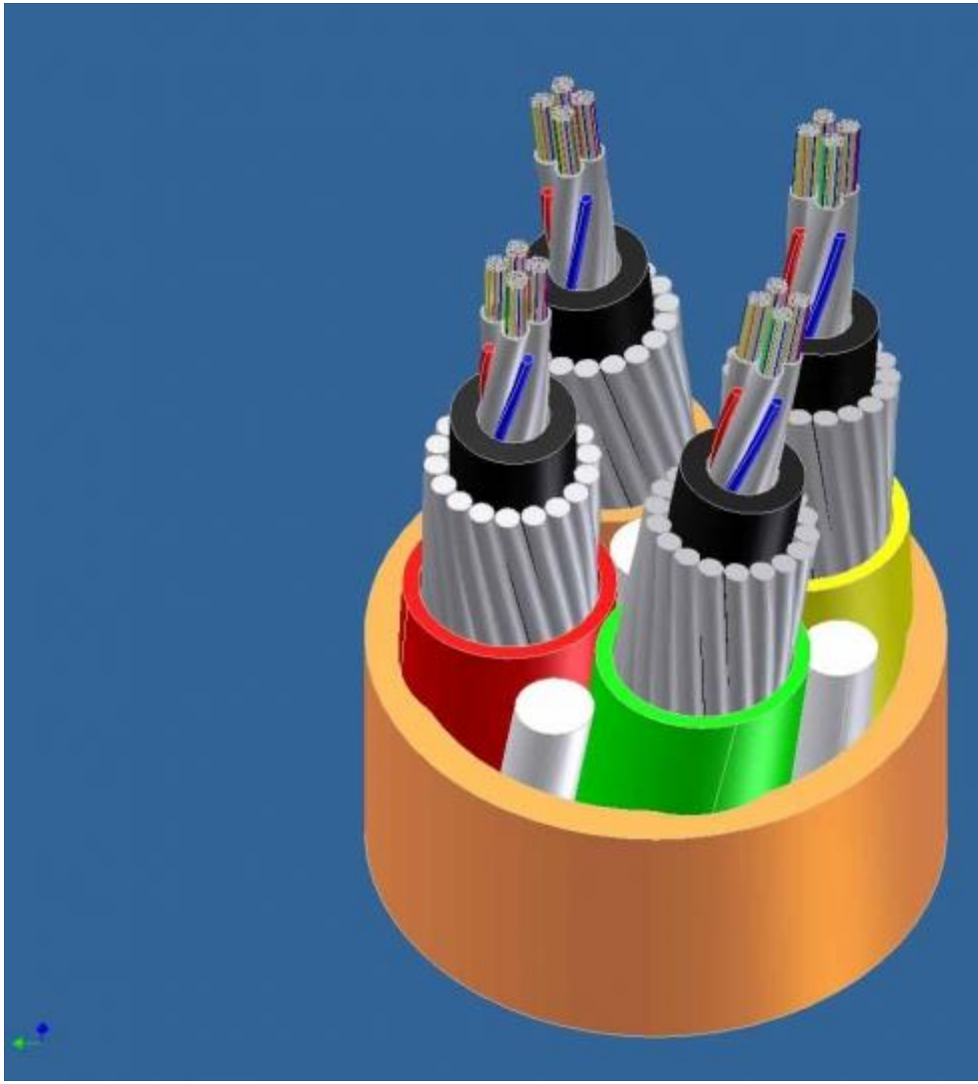
The station will connect Canada to Europe and the United States via a 12,200km undersea network. The US$850,000,000 network, known as 360atlantic, will be the first transatlantic fibre optic cable with a direct landing site in Nova Scotia.

Fibre Optic Cables



This Lucent fiber-optic cable holds 288 fibers, which was a record-high fiber count in 1996. Cables with more than a thousand fibers have since been developed.

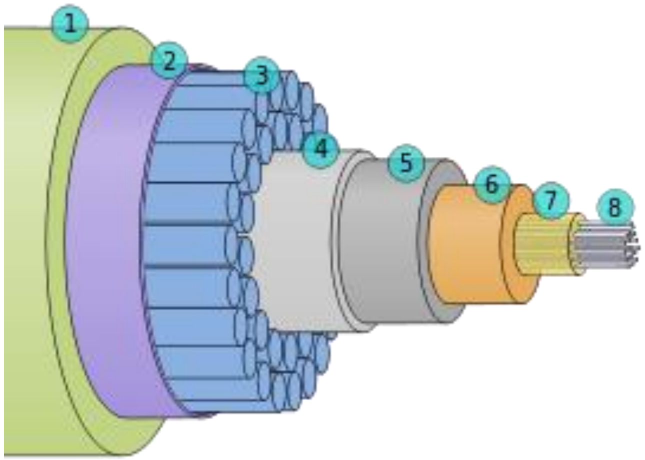
768 fibre subsea optical fibre cable



A riser cable containing 768 fibres, developed by Nexans Norway, is claimed to be a world record with regards to number of fibres. Feb 2013

The Race for numbers of fibres has reduced due to greatly improved technology

- A cross section of the shore-end of a modern submarine communications cable. 1 – Polyethylene 2 – Mylar tape 3 – Stranded steel wires 4 – Aluminium water barrier 5 – Polycarbonate 6 – Copper or aluminium tube 7 – Petroleum jelly 8 – Optical fibers



Laying Optical Fibre

Optical Fibre Structures

- Only the core and cladding are important for light propagation.
- The core and cladding are typically made of silica glass
- The core has a higher refractive index to confine light inside. Figure 4.1
- The cladding has a slightly lower refractive index, typically between a fraction of 1% and a few percent
- Most fibres have a cladding diameter of around 125 microns
- The outside cladding has several layers and is designed to prevent the fibre surface from being scratched or cut.

Optical fibres
Remember the difference

Single Mode　　　　Multi Mode

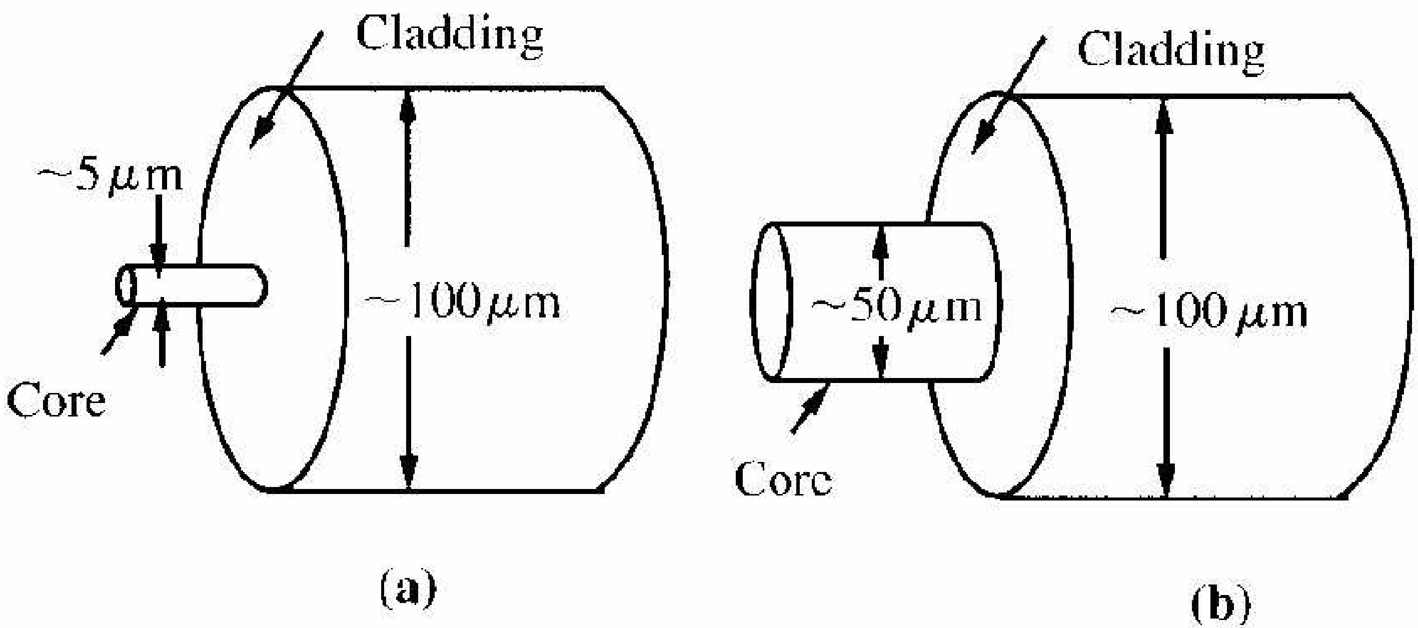


Figure 4.1 Basic structures of (*a*) single-mode and (*b*) multimode optical fibers.

Optical fibres

- When a lightwave propagates through a fibre core it can have different transverse field distributions over the fibre cross section, these are known as transverse modes
- Several transverse modes are illustrated in figure 4.2
- In general, different transverse modes travel at different speeds, this results in dispersion and is undesirable
- Fibres that allow propagation of only one mode are called single mode fibres (SMF)
- Fibres that allow propagation of multiple transverse modes are called multimode fibres (MMF)

Transverse Modes

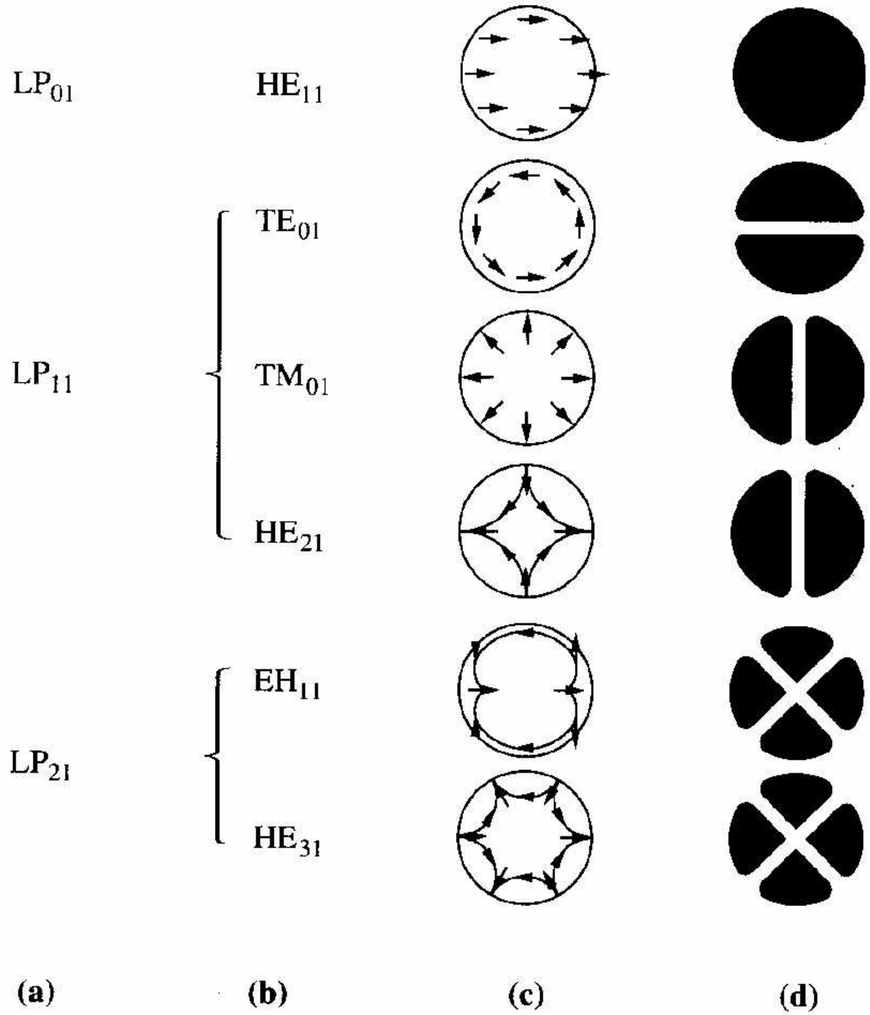


Figure 4.2 Some examples of low-order transverse modes of a step-index fiber. (*a*) Linear polarized (LP) mode designations, (*b*) exact mode designations, (*c*) electric field distribution, and (*d*) intensity distribution of the electric field component E_x.

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Cut-off wavelength

- The key in fibre design to having single-mode propagation is to have a small core diameter
- This can be understood from the dependence of the cut-off wavelength λ_c of the fibre on the core diameter
- The cut-off wavelength is the wavelength above which there can be only one single transverse mode.

$$\boxed{\lambda_c = \frac{2\pi a}{V}(n_1^2 - n_2^2)^{1/2}} \qquad \textbf{[4.1]}$$

Cut-off wavelength

- Cut-off wavelength

$$\lambda_c = \frac{2\pi a}{V}(n_1^2 - n_2^2)^{1/2} \qquad [4.1]$$

- Where the normalised frequency V = 2.405 for step-index fibres, ‘a’ is the core radius; n_1 and n_2 are the refractive indices of the core and cladding, respectively
- The equation shows that a small core radius gives a small cut off frequency
- Typically the core diameter is about 10 microns for single mode and 50 microns for multimode fibres

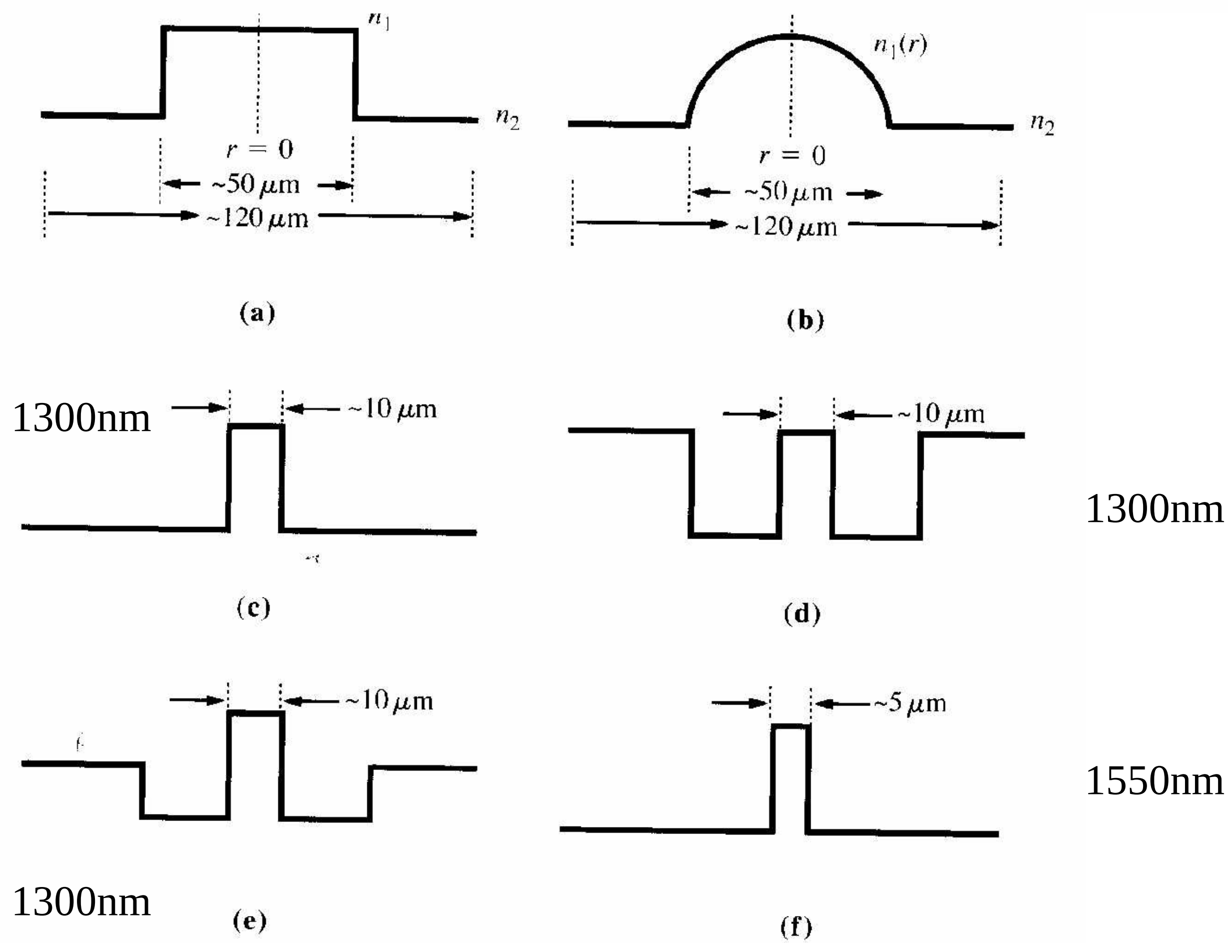
Mode field diameter

- When the core diameter is not much larger than the wavelength, there is significant power in the cladding.
- It is therefore necessary to define another parameter called the **mode field diameter** (MFD).
- It is the **root mean square** (RMS) width of the field if the field is gaussian

Refractive index profile

- Optical fibres can also vary in refractive index distribution over the core and cladding of the fibre.
- Figure 4.3a and 4.3b show two basic types of multimode fibres
- The motivation for graded index fibres is to equalise the group velocities of different propagation modes for minimal dispersion
- For single mode fibres, there are many types of refractive index profiles. Important examples are depicted in figure 4.3c-j

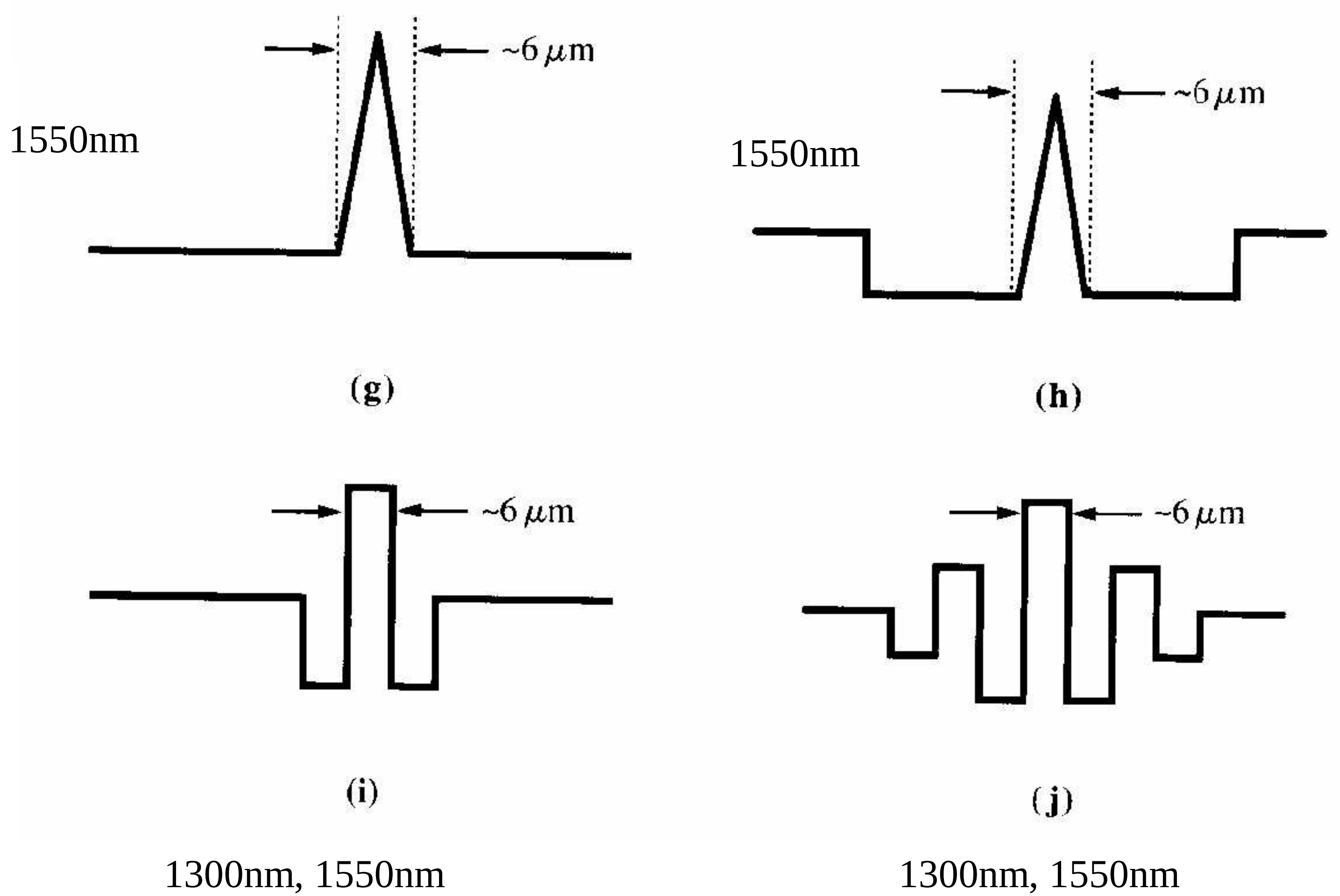
Figure 4.3 Refractive index profiles of (*a*) step-index multimode fibers, (*b*) graded-index multimode fibers, (*c*) match-cladding single-mode fibers, (*d*)–(*e*) depressed-cladding single-mode fibers, (*f*)–(*h*) dispersion-shifted fibers, and (*i*)–(*j*) dispersion-flattened fibers.



Refractive index profile

- Figure 4c has the regular step index profile. Both the core and cladding have constant refractive indices
- fibres of types d and e have different refractive indices in the cladding region. These are called depressed-cladding (DC) fibres.
- In contrast, type c fibres are called matched cladding (MC) fibres
- These three types of fibres are used as single mode fibres at 1300nm

Figure 4.3 Refractive index profiles of *(a)* step-index multimode fibers, *(b)* graded-index multimode fibers, *(c)* match-cladding single-mode fibers, *(d)*–*(e)* depressed-cladding single-mode fibers, *(f)*–*(h)* dispersion-shifted fibers, and *(i)*–*(j)* dispersion-flattened fibers.



Refractive index profile

- Figure 4.3f has a small core diameter; figures 4.3g and 4.3h a triangle-shaped core refractive index profile is used, the core diameter is about 6 microns
- These three fibres have a higher waveguide dispersion so that the total fibre dispersion is zero at 1550nm
- They are called **dispersion-shifted fibres**

Refractive index profile

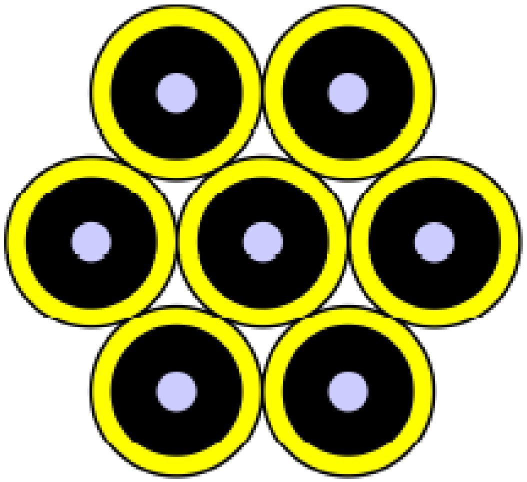
- The fibres in figures 4.3i and 4.3j have up and down refractive index profiles. They are called multi-cladding or dispersion-flattened fibres
- These fibres have flat fibre dispersion characteristics over the 1300-1500nm wavelength range.

Technical approaches to space division multiplexing (SDM)

- SDM is nowadays taken to refer to multiplexing techniques that establish multiple spatially distinguishable data pathways through the same fibre.
- The primary technical challenge given the more intimate proximity of the pathways is management of cross-talk.

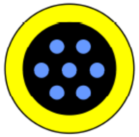
(a) Fibre bundles

- (a) Fibre-bundles composed of physically-independent, single-mode fibres of reduced cladding dimension could provide for increased core packing densities relative to current fibre cables,

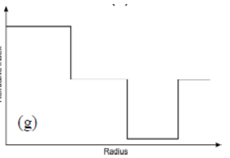


(a)

(b) Multi core fibre (MCF)



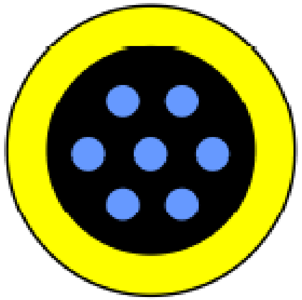
(b)



- In the case of multicore fibre (MCF) in which the distinguishable pathways are defined by an array of physically-distinct single-mode cores (Figure (b))
- the simplest way to limit cross-talk is to keep the fibre cores well-spaced. Small variations in core properties, either deliberately imposed across the fibre cross-section, or due to fabrication/cabling, can also reduce cross-coupling along the fibre length.
- Using trench-type core refractive index profiles matched to standard SMF (Figure (g)), to better confine the mode, it has proved possible to reduce core-to-core coupling to impressively low levels (<-90dB/km) for a spacing of around 40μm, enabling transmission over multi-1000km length scales.

(b) Multi core fibre (MCF)

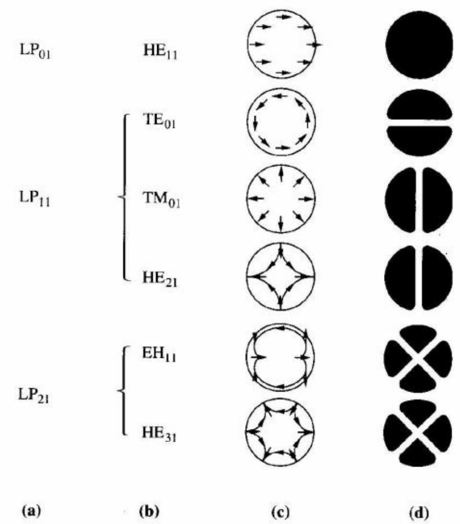
- (b) Multi core fibre (MCF) comprising multiple independent cores sufficiently spaced to limit cross-talk.
- Fibres with up to 19 cores have so far been demonstrated for long haul transmission –
- higher core counts are possible for short haul applications (e.g. datacomms) which can tolerate higher levels of cross-talk per unit length.



(b)

(c) Multi mode fibres (MMF)

- The situation is quite different for mode division multiplexed (MDM) transmission in MMF where the distinguishable pathways have significant spatial overlap and, as a consequence, signals are prone to couple randomly between the modes during propagation.
- In general the modes will exhibit differential mode group delays (DMGD) and also differential modal loss or gain.
- The energy of a given data symbol launched into a particular mode spreads out into adjacent symbol time slots as a result of mode-coupling, rapidly compromising successful reception of the information it carries.



(c) multiple-input multiple-output (MIMO) techniques

- Crosstalk occurs when light is coupled from one mode to another and remains there upon detection.
- Inter-symbol interference occurs when the crosstalk is coupled back to the original mode after propagation in a mode with different group velocity.
- As in wireless systems, equalization utilizing multiple-input multiple-output (MIMO) techniques is required at the receivers to mitigate these linear impairments.
- MIMO signal processing is already widely used in current coherent optical transmission systems with polarization division multiplexing (PDM) over standard single-mode fibres
- A 2x2 realization with four finite impulse response (FIR) filters recovers the signals on the two polarizations and compensates for PMD in the link

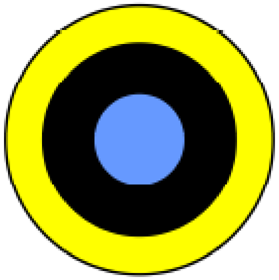
(c) Multiple-input multiple-output (MIMO) techniques

- For an MDM system with M modes, the respective algorithms would need to be scaled to 2Mx2M MIMO, requiring $4M^2$ adaptive FIR filters. (By way of comparison, the same capacity carried on M uncoupled SDM waveguides would require 4M adaptive FIR filters.)
- Thus, if we assume an equal number of taps per adaptive FIR filter and equal complexity of the adaptation algorithm, comparing a 2M×2M MIMO system on M coupled waveguides to M uncoupled SDM waveguides using PDM results in a complexity scaling as $4M^2/(4M) = M$
- To compensate differential mode group delays DMGD and mode cross-talk completely, the equalization filter length should be larger than the impulse response spread.

(c) Multiple-input multiple-output (MIMO) techniques

- Conventional MMFs with core/cladding diameters of 50/125 and 62.5/125um support more than 100 modes and have large differential mode group delays DMGDs
- They are thus are not suitable for long-haul transmission because the DSP complexity would be too high.
- Recent advancements have led to fibres supporting a small number of modes, the so-called “few-mode fibres” (FMFs), with low DMGD (see Figure (c)).
- The most significant research demonstrations have so far concentrated on the simplest FMF, which supports three modes, the LP01 and degenerate LP11 modes, for a total of 6 polarization and spatial modes (referred to as 3MF).

(c) Few Mode Fibre (FMF)

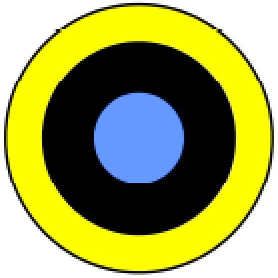


(c)

- (c) Few Mode Fibre (FMF) with a core dimension/numerical aperture set to guide a restricted number of modes – so far typically 6-12 distinct modes (including all degeneracies and polarisations).

(c) Few Mode Fibre

- To date work has focussed primarily on using the first few LP-fibre modes;
- However, work is now beginning on using other modal basis sets that exploit the true vector modes of the fibre –
- In particular on modes that carry orbital angular momentum and which may provide benefits in terms of reduced mode-coupling and associated DSP requirements



(c)

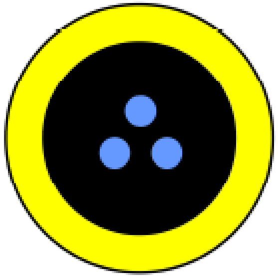
Supermodes figure (d)

(d)

- The impact of differential modal gain and loss can in principle be mitigated by strong mode-coupling over a suitable length scale relative to the amplifier spacing.
- In the Multi core fibre (MCF) case, by bringing the cores closer together to ensure strong mode-coupling, it is possible to establish supermodes defined by the array of cores, which can then be used to provide spatial information channels for MDM to which MIMO can be applied.
- This enables higher spatial channel densities for MCFs than can be obtained using isolated cores designs.

(d) Coupled-core fibres

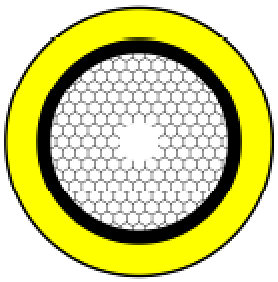
- (d) Coupled-core fibres support supermodes that allow for higher spatial mode densities than isolated-core fibres.
- MIMO processing is essential to address the inherent mode-coupling.



(d)

(e) Photonic Band Gap fibres

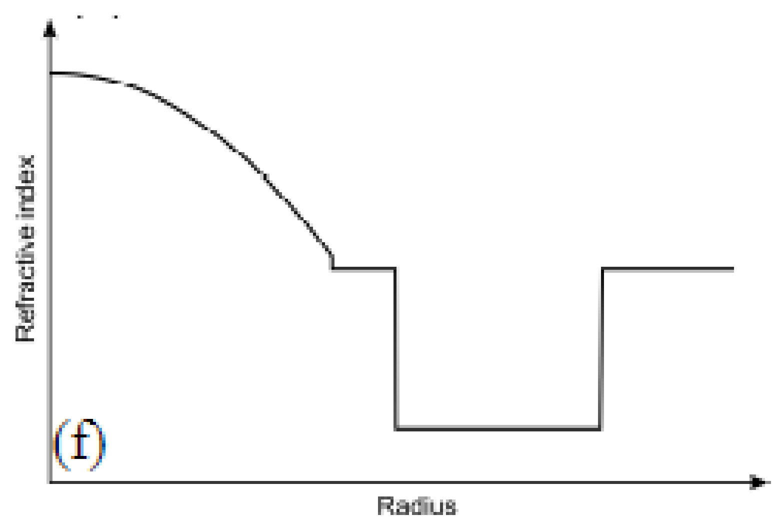
- (e) Photonic Band Gap fibres guide light in an air-core and thus have ultra-low optical nonlinearity, offer the potential for lower losses than solid core fibres (albeit at longer transmission wavelengths around 2μm rather than 1.55μm).
- Work is underway to understand whether such fibres can support MDM and to establish their practicality for high capacity communications.



(e)

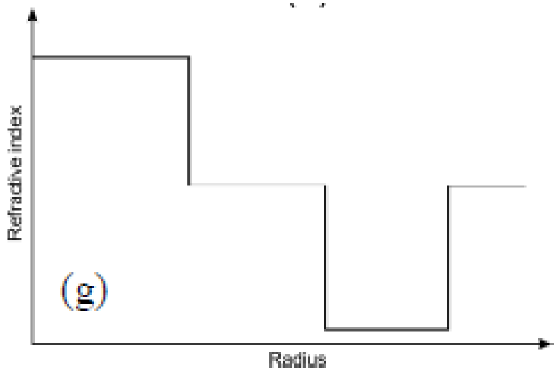
(f) Refractive index profile of a GI core

- (f) Refractive index profile of a GI core design providing low differential mode group delays (DMGD) and low mode-coupling for long haul FMF transmission



(g) Core refractive index design

- (g) Core refractive index design incorporating a trench profile to reduce cross-talk and thus allow closer core separations in MCF



Fibre attentuation

- Material absorption loss:
  - Intrinsic loss is caused by atomic resonances of fibre material as shown in figure 4.4. The absorption occurs in both the infra-red and ultraviolet ranges.
  - Extrinsic absorption is caused by the atomic resonances of external particles in the fibre. One important extrinsic absorption loss is due to water or the O-H bond that has a resonant frequency at 2.8 microns.

Intrinsic attenuation

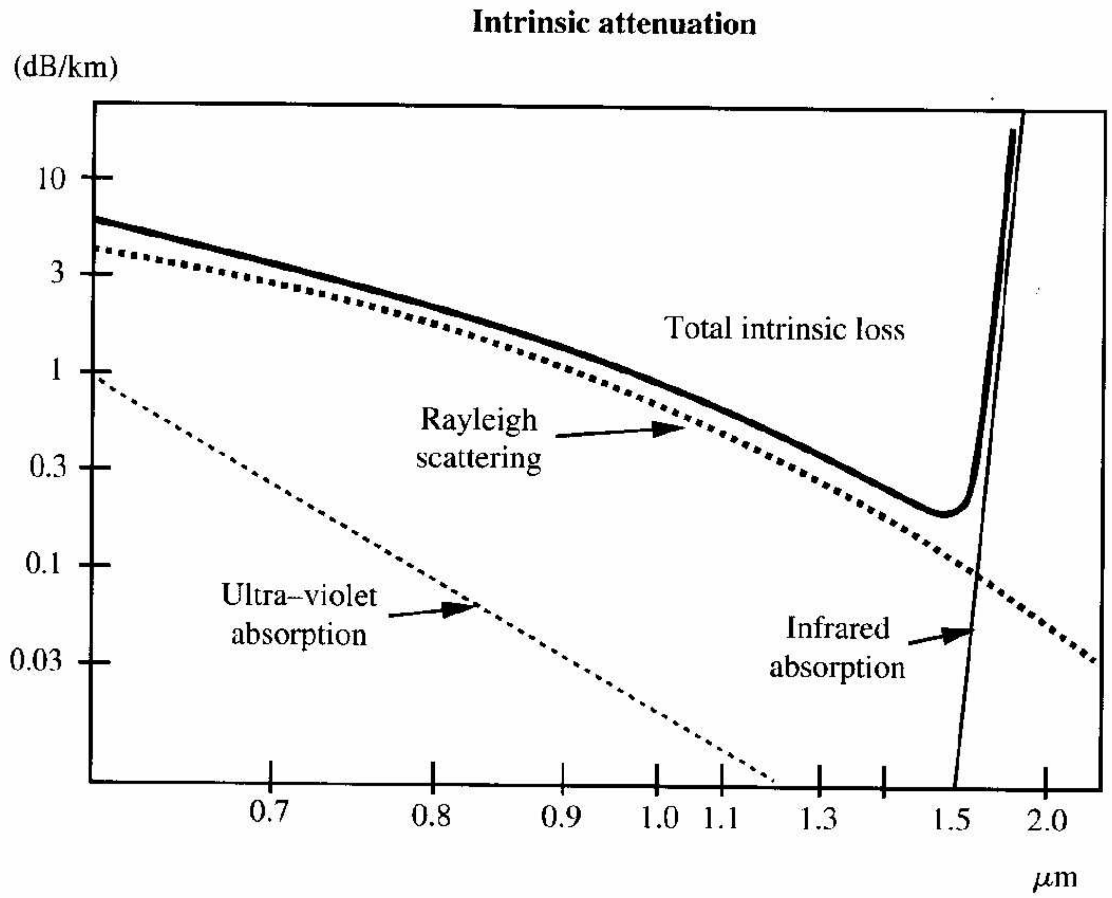
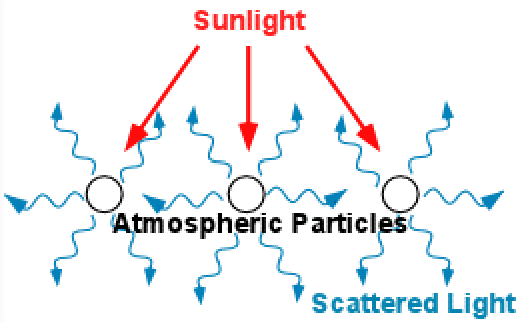
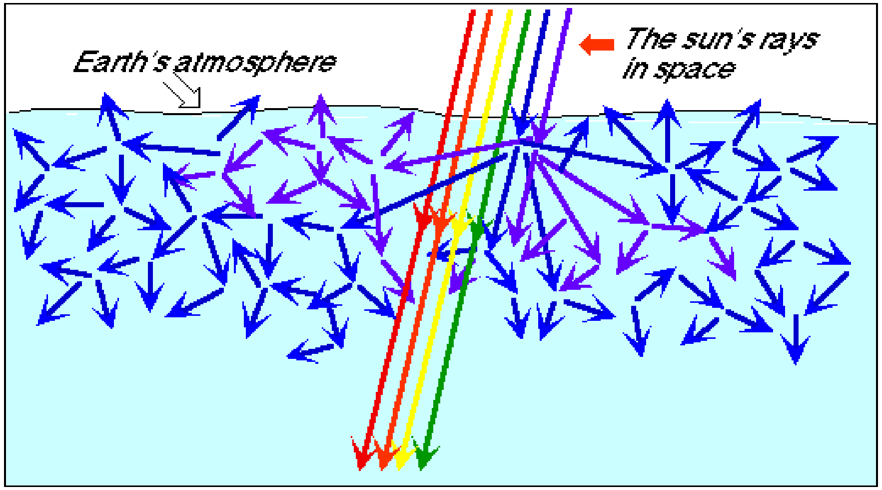


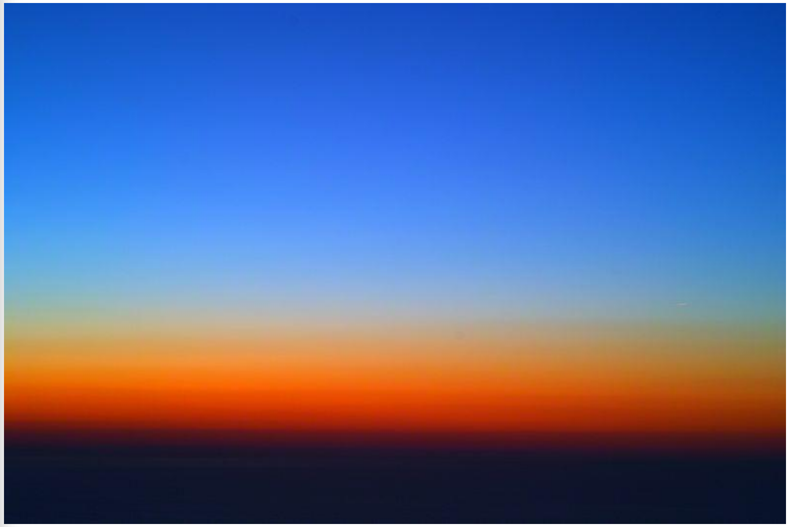
Figure 4.4 Intrinsic attenuation in optical fibers.

Atmospheric Rayleigh Scattering





Shorter wavelengths are scattered more intensely than longer wavelengths. This means that blue light has a higher probability of being scattered than red light.



Rayleigh scattering is more evident after sunset. This picture was taken about one hour after sunset at 500m altitude, looking at the horizon where the sun had set.

Extrinsic attenuation

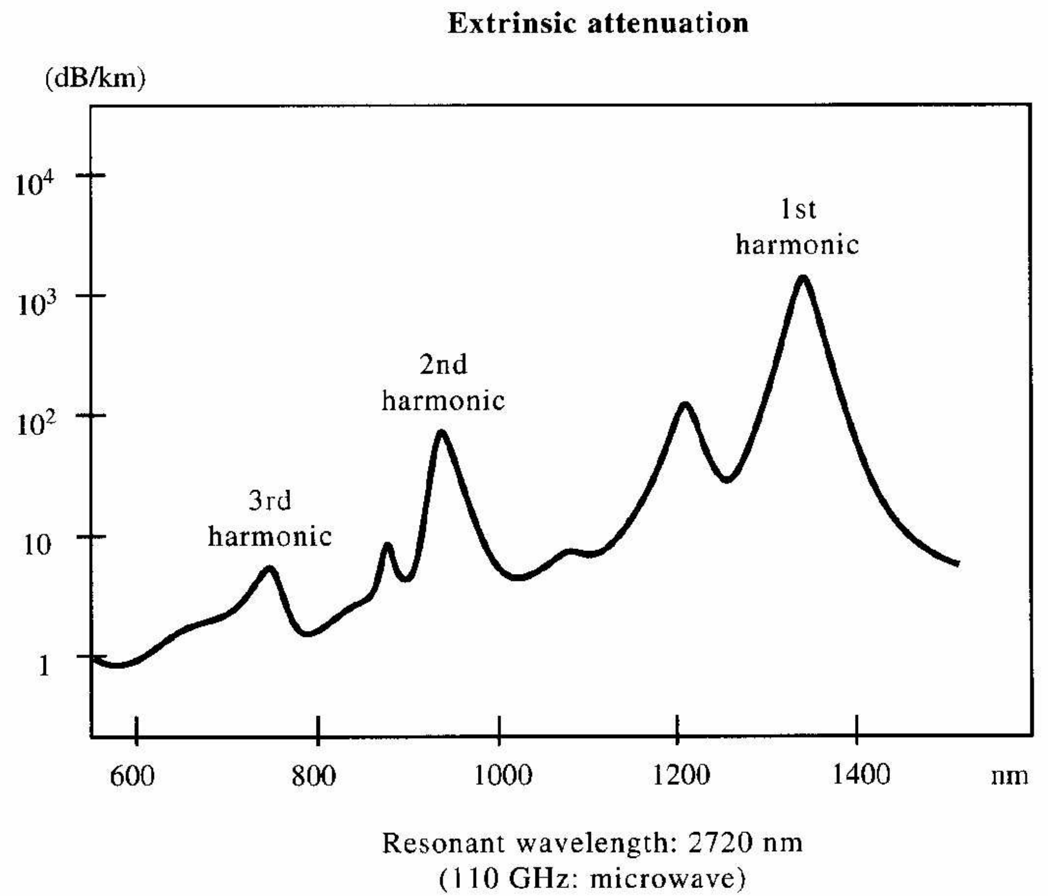
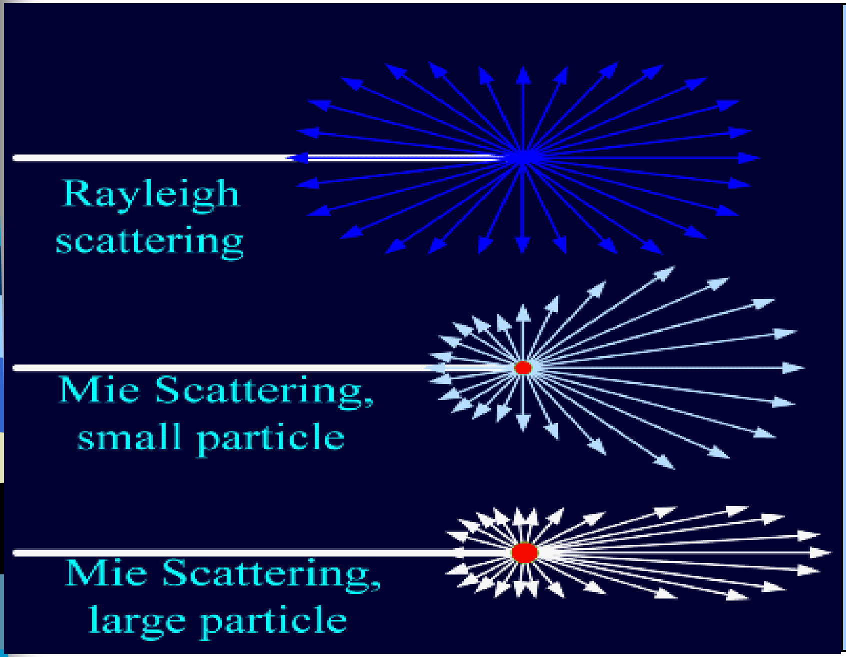
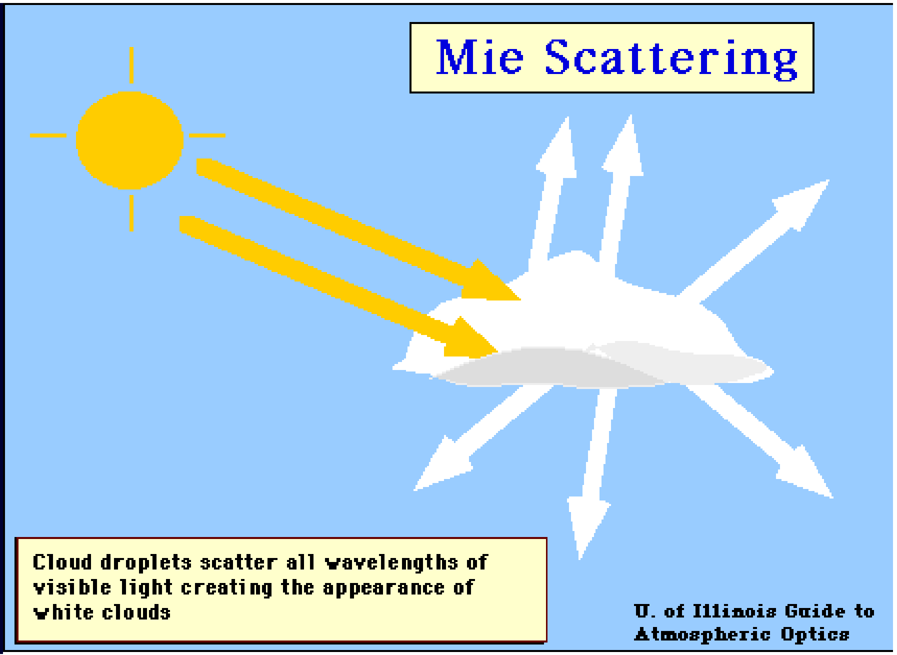


Figure 4.5 Extrinsic attenuation in optical fibers.

Mie Scattering





The scattering of light from larger particles is known as Mie Scattering.

The larger particles scatter the light in the forward direction. The larger a particle, the more intense the light scattered in the forward direction.

Mie Scattering is not strongly wavelength dependent. It also produces a white glare around the particle. This is the reason fog or mist appears to be white.

Scattering Loss

- There are four types of scattering loss in optical fibres: Raleigh, Mie, Brillouin and Raman
- Raleigh is the most important loss and is shown in figure 4.4, it can be expressed as:

$$\alpha_R = c_R \frac{1}{\lambda^4} \text{ [dB/km]} \qquad \textbf{[4.2]}$$

- Where c_R is called the Raleigh scattering coefficient.
- Practical measured values are shown in figure 4.6, it is a function of the refractive index difference between the core and the cladding, core diameter and the type of doped materials

Raleigh scattering loss

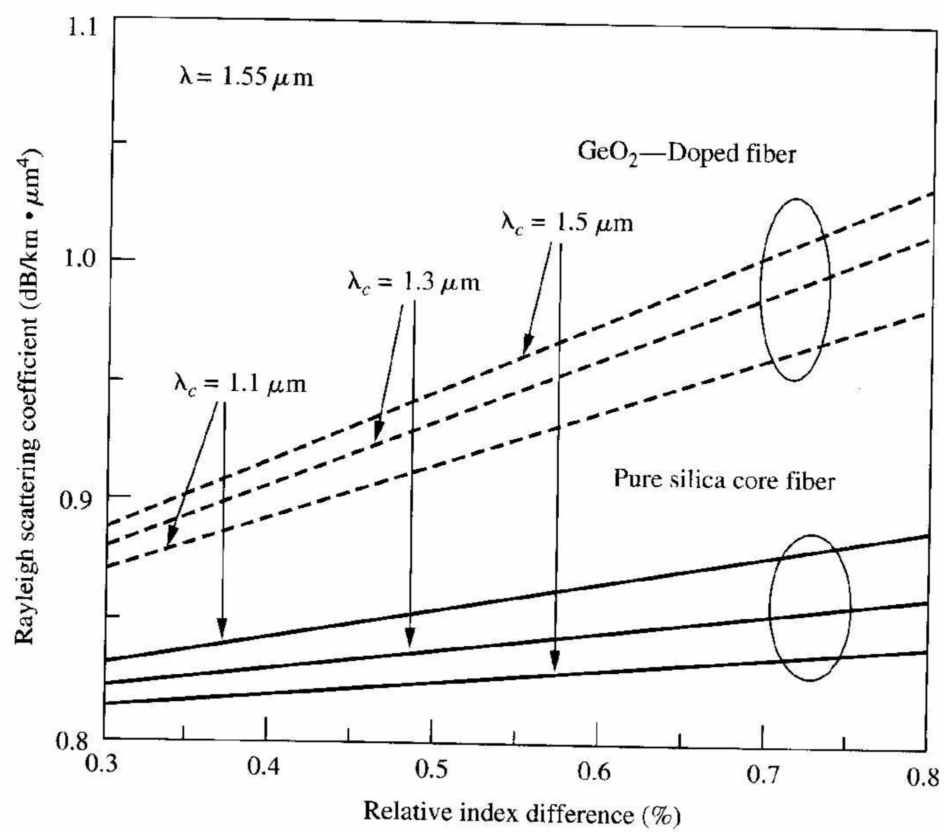


Figure 4.6 Rayleigh scattering loss coefficient.

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Fibre Loss

- In general. The larger the refractive index difference, the larger the Rayleigh scattering loss.
- The total loss including the material loss and Raleigh scattering loss is shown in figure 4.7
- Infra-red absorption is negligible compared to the Raleigh scattering
- There are low attentuation windows at 1300 nm and 1550 nm; therefore most light sources are operated at these wavelengths for minimal attenuation.

Total attenuation

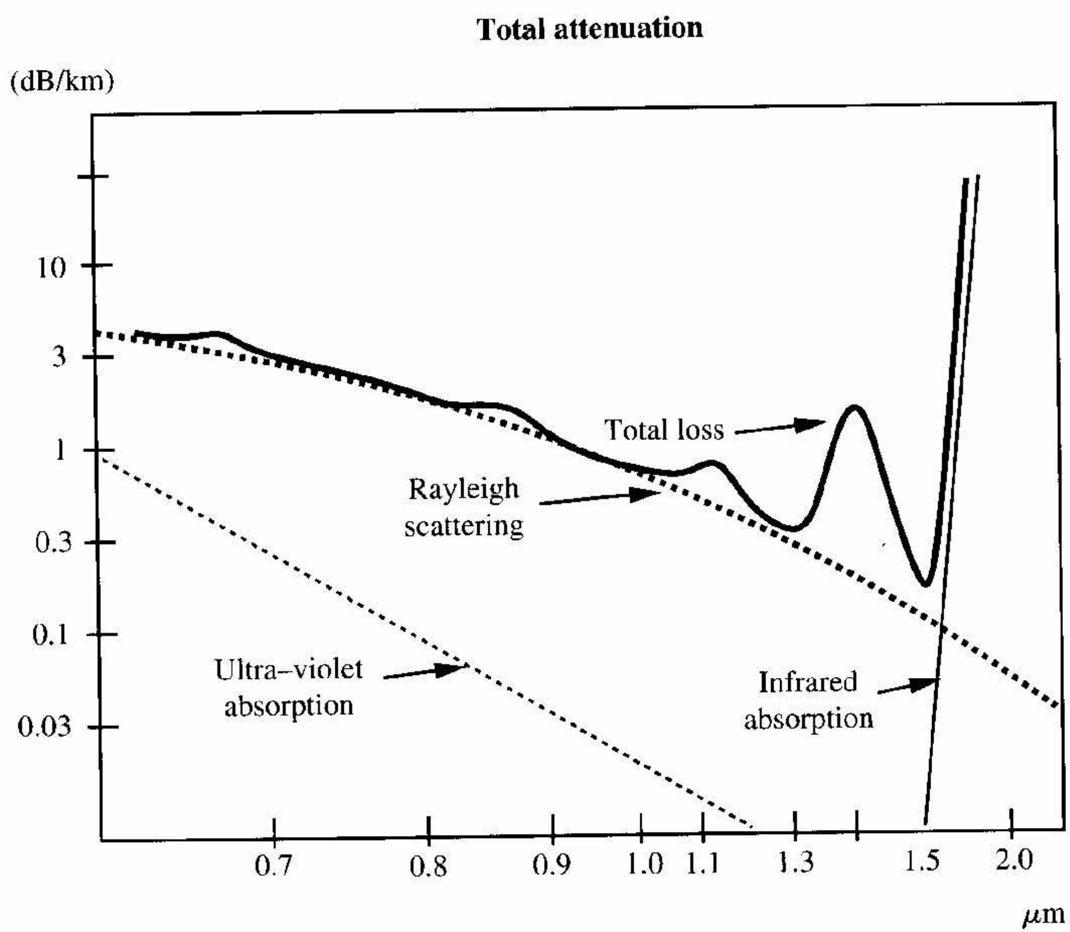
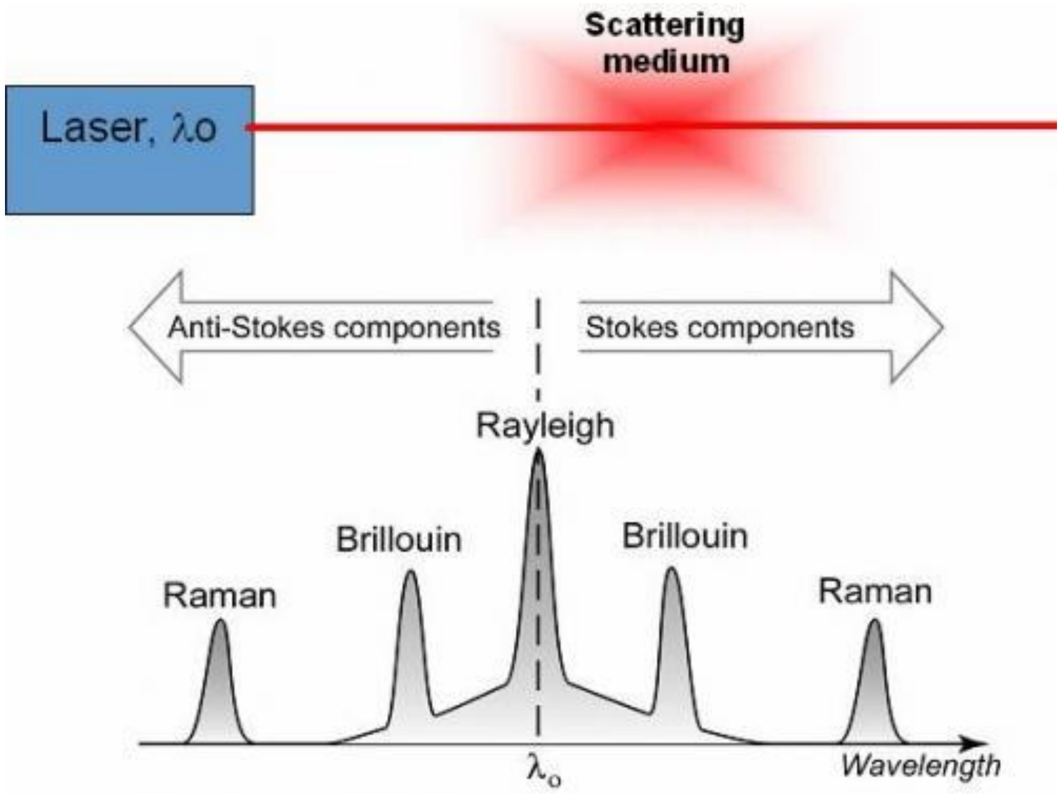


Figure 4.7 Total fiber attenuation. The extrinsic absorption due to the O-H bond of water varies with the fiber manufacturing process.

Fibre losses

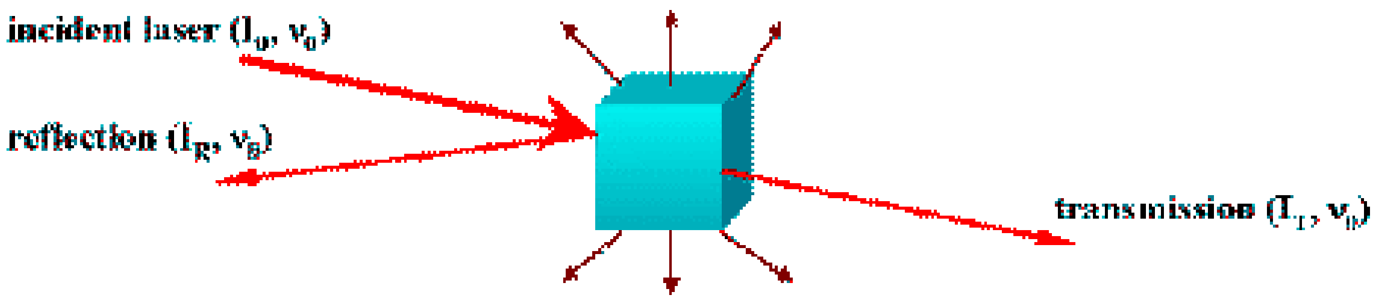
- Brillouin and Raman scattering only become significant at high power, typically 100W for Brillouin and 1W for Raman.
- Bending loss occurs at bends and curves because of evanescent modes generated. This is usually insignificant.
- Coupling and splicing loss occurs at a junction of two fibres

Brillouin & Raman Scattering



The Brillouin interaction results in the generation of scattered light (Brillouin component) which shows a frequency shift compared to the light causing the interaction. This shift can be attributed to the presence of inhomogeneities associated to acoustic waves in the silica (acoustic phonons)

Summary



Scattered Radiation

Mie	Rayleigh	Brillouin	Raman
(ν_0)	(ν_0)	($\nu_0 \pm \Delta\nu_B$)	($\nu_0 \pm \Delta\nu_R$)
particles	particles	Molecular translations	Molecular rotations, vibrations, ele. transitions
	$I_S \sim 10^{-3} I_0$	$\Delta\nu_B < 0.1\ cm^{-1}$	$I_R \sim (10^{-6}-10^{-9})I_0$ $\Delta\nu_R < 10^4\ cm^{-1}$

Coupling and splicing loss

- Extrinsic loss:
  - Misalignment in the core centre
  - Tilt
  - End gap
  - End face quality
- Intrinsic loss
  - Core ellipticity
  - Mismatch in refractive index
  - Mismatch in mode field diameter
- Typically, coupling loss is around 0.2 dB and splicing loss is around 0.05 dB

Power Budget

- Given the required received power and available transmission power, the upper limit of the allowable power loss from transmission is called the power budget
- Specifically, if the transmission power is P_{tx} and the minimum required receiving power is P_{min} the power budget is the ratio:
- Power Budget = P_{tx} / P_{min}
- Power Budget[dB] = P_{tx} [dB]- P_{min} [dB]
- If P_{tx} = 1mW and P_{min} = 0.1 micro. The power budget is : $10\log_{10}10^4 = 40$bB

Power Budget

- The total loss in a transmission line must be below the power budget
- Attenuation is expressed in terms of dB/km, thus we need:

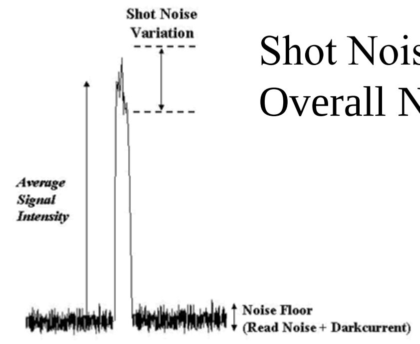
$$\alpha_{fiber} L + \alpha_{coupling} N + \text{other loss} \leq \text{Power budget [dB]} \qquad \textbf{[4.5]}$$

- Where N is the total number of connections in the transmission line.

$$\boxed{L_{max} = \frac{1}{\alpha_{fiber}} \left\{ 10 \log_{10} P_{tx} - 10 \log_{10} P_{min} - \text{other loss [dB]} \right\}} \qquad \textbf{[4.6]}$$

Dependence of receiver sensitivity on bit rate

- In digital communication, the minimum required received power increases as the transmission bit rate increases, in most cases they are linearly proportional
- As the bit rate increases, the bandwidth of the signal increases. Therefore, the receiver needs to have a larger bandwidth to receive the signal
- As the receiver bandwidth increases, more noise power passes through
- To maintain the same received SNR, the signal power thus should be proportionally increased



Shot Noise is due to the 'particle' nature of photons.

Overall Noise = $\sqrt{(readnoise)^2 + (darknoise)^2 + (shotnoise)^2}$

Receiver sensitivity

- The reciever sensitivity is linearly proportional to the transmission bit rate when the total receiver noise is dominated by shot noise. In this case:

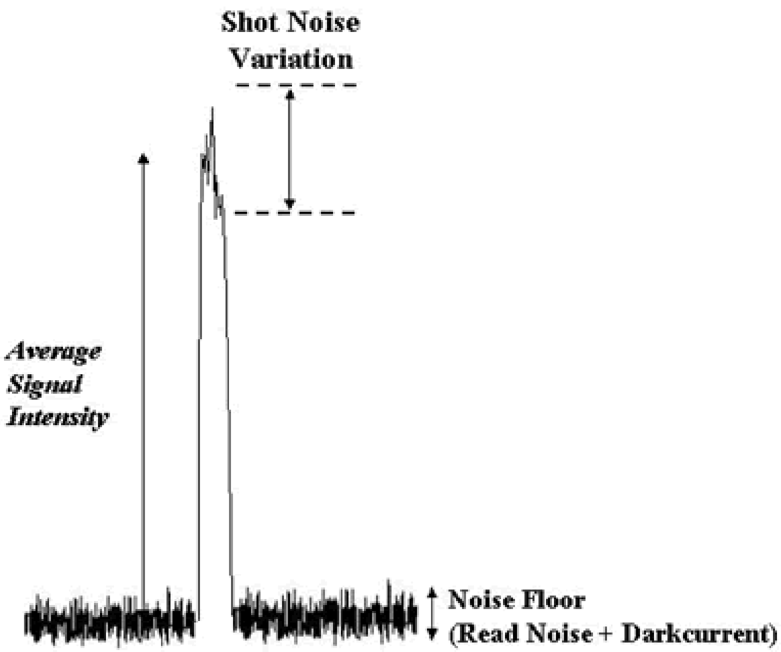
$$P_{min} = B \times \frac{P_0}{B_0} \quad \text{or} \quad P_{min}[\text{dB}] = P_0[\text{dB}] + 10\log_{10}(B/B_0) \qquad \textbf{[4.7]}$$

where B is the bit rate, and P_0 is the receiver sensitivity at bit rate B_0. Substituting Equation (4.7) into Equation (4.6) we have

$$\begin{aligned} L_{max} &= \frac{1}{\alpha_{fiber}}[(P_{tx} - P_0)\text{dB} - 10\log_{10}(B/B_0) - \text{other loss}] \\ &= L_{max,0} - \frac{10}{\alpha_{fiber}}\log_{10}(B/B_0). \end{aligned} \qquad \textbf{[4.8]}$$

This equation is the attenuation limit, or how large L_{max} can be at a given B. Figure 4.8 illustrates a typical attenuation limit according to the equation.

Receiver sensitivity



Shot Noise is due to the ‘particle’ nature of photons.

Overall Noise = $\sqrt{(readnoise)^2 + (darknoise)^2 + (shotnoise)^2}$

Attenuation limit

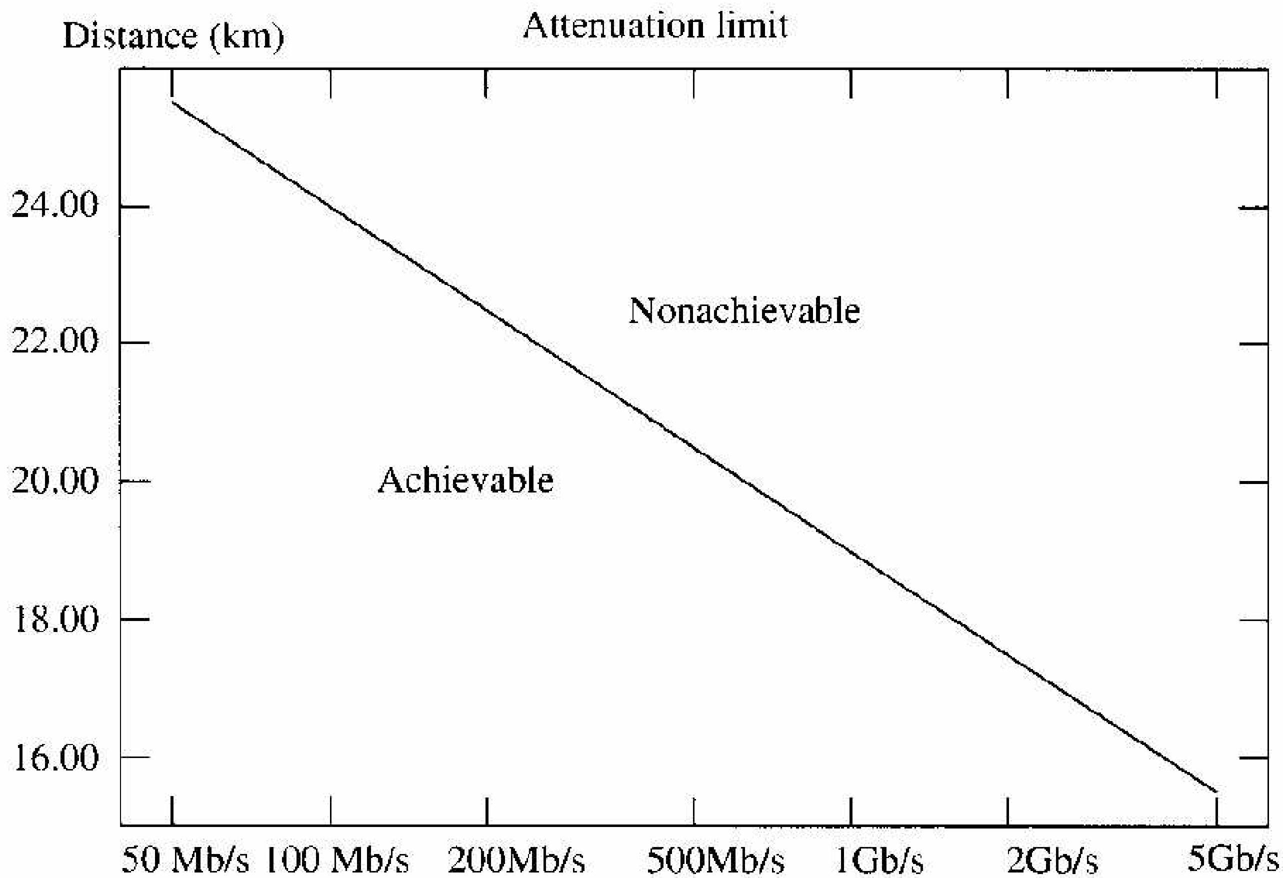


Figure 4.8 An attenuation limit at $\alpha_{fiber} = 2$ dB/km.

Light propagation in optical fibres

- Dispersion is a phenomenon in which photons of different frequencies or modes propagate at different speeds
- As a result the light pulse gets broader as it propagates along the fibre
- The geometric optics model for fibre propagation is illustrated in figure 9
- From Snell's law, each ray will go partially into the cladding region or be totally reflected back depending on its incident angle at the core/cladding boundary

Geometric optics

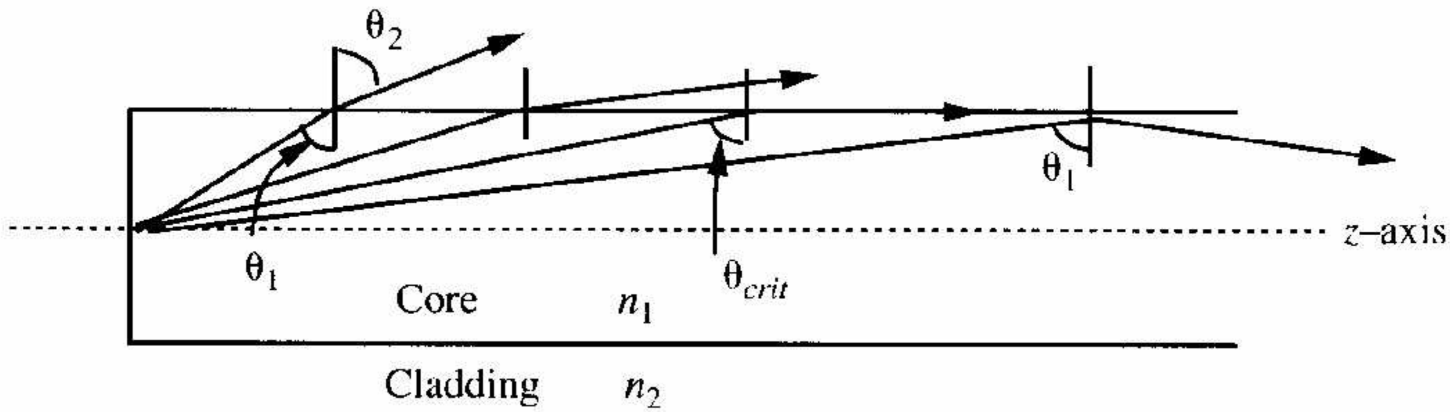
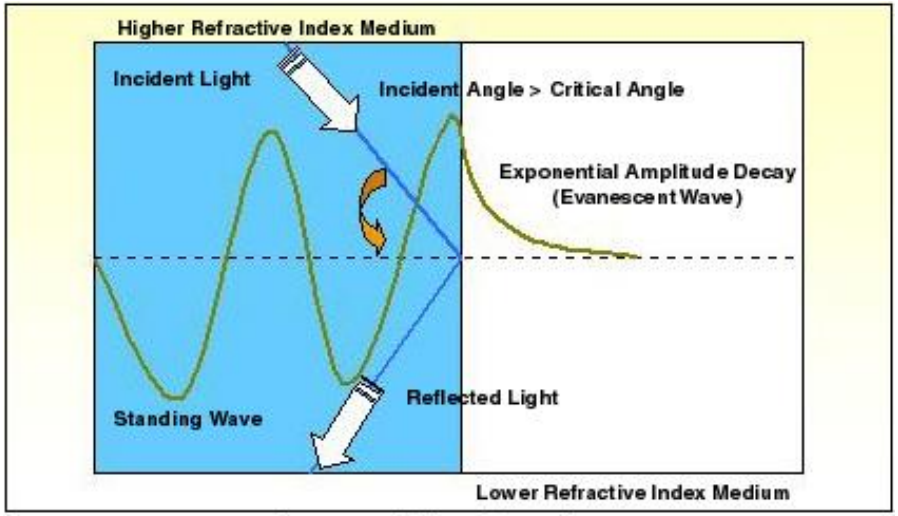


Figure 4.9 Light propagation using geometrical optics.



Evanescent Wave Generation

Snell's law

- Snell's law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \qquad [4.9]$$

- Where n_1 and n_2 are the refractive indices of the core and cladding respectively
- Because $n_1 > n_2$, a complete internal reflection is possible if

$$\theta_1 > \sin^{-1}\left(\frac{n_2}{n_1}\right) \stackrel{\text{def}}{=} \theta_{crit}. \qquad [4.10$$

- The ray will be totally reflected back into the core
- The ray will propagate along the fibre without loss if the incident angle satisfies equation 4.10

Dispersion

- For rays with different $\theta_1 > \theta_{crit}$ we have different z-component velocities
- Specifically, for a ray of θ_1 its z component velocity is:

$$v_z = \frac{c}{n_1}\sin(\theta_1). \quad [4.11]$$

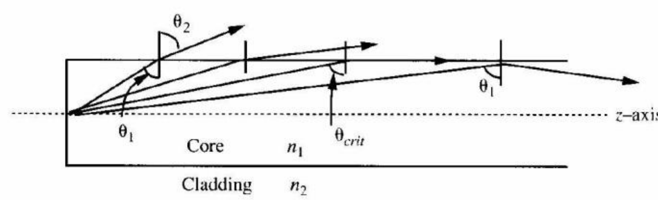


Figure 4.9 Light propagation using geometrical optics.

- This velocity dependence on θ_1 results in different propagation delays or dispersion
- To reduce dispersion, graded index fibres can be used

Dispersion and propagation

- Ray propagation in a graded index fibre is illustrated in figure 4.10
- The graded index fibres can equalise the propagation delay of different propagation rays and greatly reduce the fibre dispersion
- Equation 4.10 gives the condition of propagatable rays.
- When θ_{crit} is large or n_2 is very close to n_1 the incident ray has to be closely parallel to the fibre axis
- Therefore it is more difficult to inject the light into the fibre for propagation.

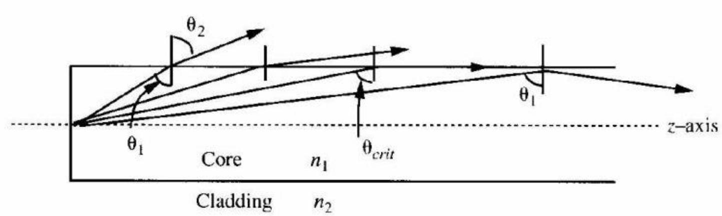


Figure 4.9 Light propagation using geometrical optics.

Graded Index propagation

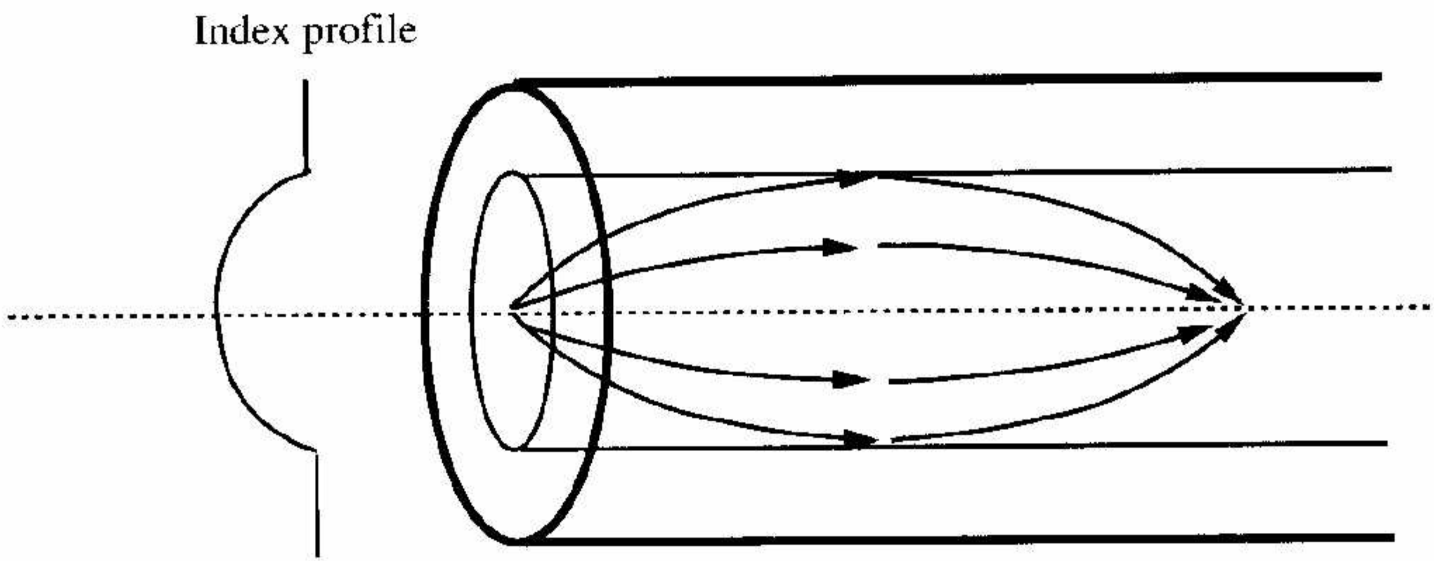


Figure 4.10 Ray propagation in a graded-index fiber.

Numerical Aperture

- The ease of coupling a lightwave into a fibre is quantified by the Numerical Aperture, defined by:

$$NA \stackrel{\text{def}}{=} \sqrt{n_1^2 - n_2^2} \qquad \textbf{[4.12]}$$

has been used. Because n_1 is close to n_2 in optical fibers, $n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2) \approx 2n_2^2[(n_1 - n_2)/n_2]$. NA in Equation (4.12) can thus be approximated by

$$NA \approx \left[(2n_2^2)\left(\frac{n_1 - n_2}{n_2}\right)\right]^{1/2} = n_2(2\Delta)^{1/2} \qquad \textbf{[4.13]}$$

where

$$\Delta \stackrel{\text{def}}{=} \frac{n_1 - n_2}{n_2} \approx \frac{n_1 - n_2}{n_1} \qquad \textbf{[4.14]}$$

is the ratio of the refractive index difference.

Numerical Aperture

- The physical meaning of the NA can be explained as follows.

$$\Omega = \frac{\text{cone area}}{d^2} = 2\pi[1-\cos(\theta_{in})] = 4\pi\sin^2(\frac{\theta_{in}}{2}) \approx \pi\sin^2(\theta_{in})$$

when $\theta_{in} \ll 1$.From Figure 4.11 and Equation (4.10),

$$\sin(\theta_{in}) = n_1\cos(\theta_{crit}) = n_1[1-\sin^2(\theta_{crit})]^{1/2} = (n_1^2 - n_2^2)^{1/2} = NA. \quad \textbf{[4.15]}$$

Therefore,

$$\Omega \approx \pi(n_1^2 - n_2^2) = \pi NA^2. \quad \textbf{[4.16]}$$

This shows that the larger the NA, the larger the solid angle within which incident light can propagate.

Numerical Aperture

$$\Omega \cong \pi NA^2$$

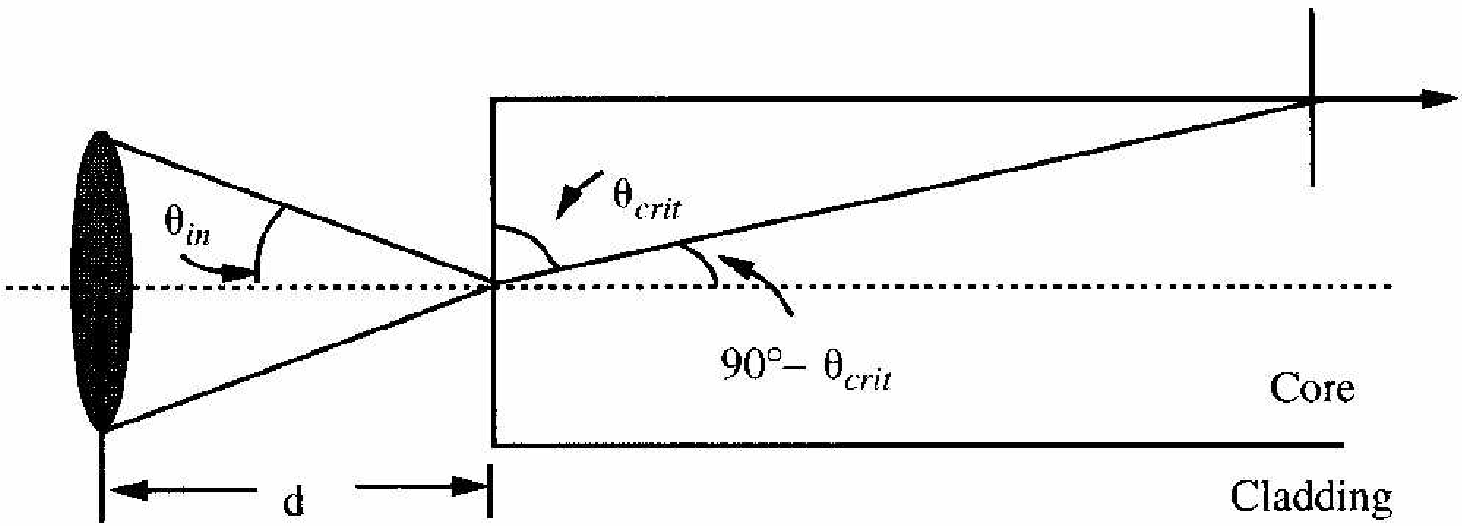


Figure 4.11 The physical meaning of numerical aperture.

$$\theta_1 > \sin^{-1}\left(\frac{n_2}{n_1}\right) \stackrel{\text{def}}{=} \theta_{crit}. \quad \textbf{[4.10}$$

Propagation Modes

- The wave function of a propagation mode is expressed as:

$$\Psi_i(r, \phi, z) = A_i(r, \phi)e^{j(\omega t - \beta_{zi} z)} \quad \textbf{[4.17]}$$

- Where *i* is the index to propagation mode ψ_i , $A_i(r,\phi)$ is the transverse field distribution and β_{zi} is the z axis propagation constant.
- As the equation shows, the wave function is a function of time t and spatial parameters r, ϕ and z, ie, cylindrical coordinates
- The factor $e^{j(wt - \beta zi.z)}$ describes a traveling wave propagating along the fibre (z) axis

Transverse Modes

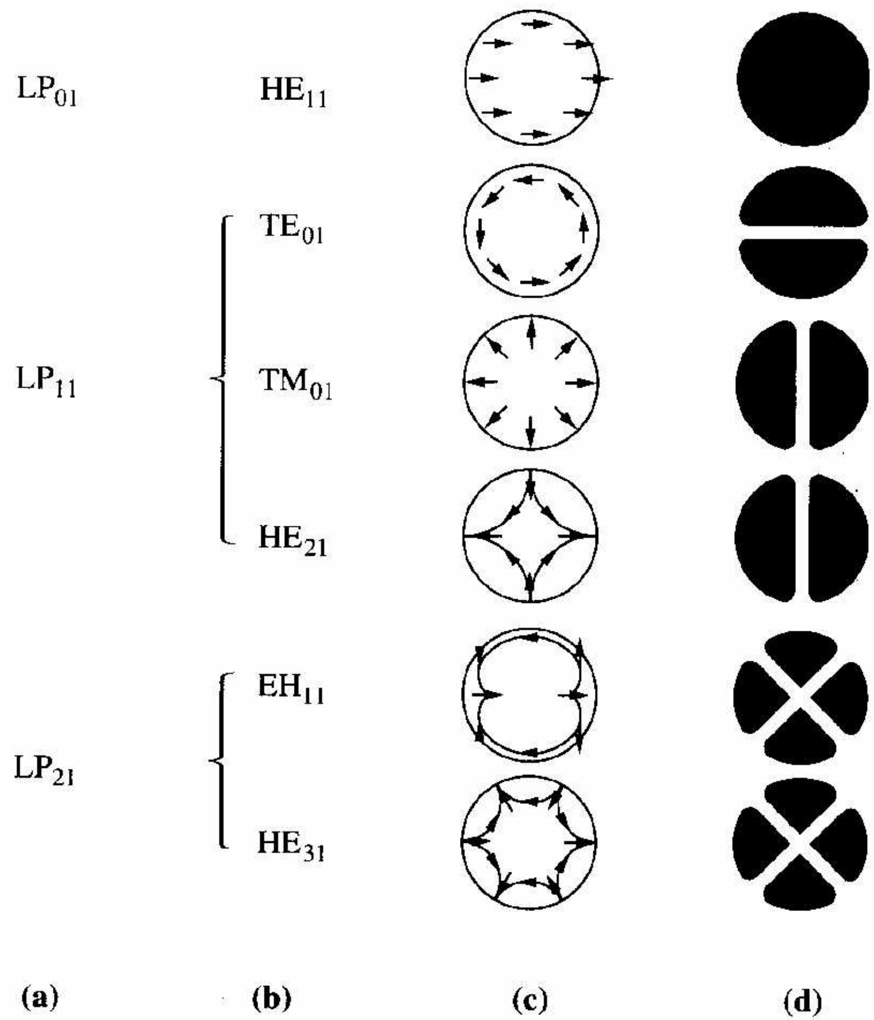


Figure 4.2 Some examples of low-order transverse modes of a step-index fiber. (*a*) Linear polarized (LP) mode designations, (*b*) exact mode designations, (*c*) electric field distribution, and (*d*) intensity distribution of the electric field component E_x.

Source: Reprinted, by permission, from Senior, *Optical Fiber Communications: Principles and Practice*, 2nd ed. [8]. ©1992 by Prentice-Hall International (UK) Ltd.

$$\Psi_i(r, \phi, z) = A_i(r, \phi) e^{j(\omega t - \beta_{zi} z)} \quad \textbf{[4.17]}$$

z - Direction Propagation constant

- From the concept of propagation modes, β_{zi} is the z axis propagation constant and satisfies the dispersion equation:

$$\boxed{\beta_1^2 = \left(\frac{n_1\omega}{c}\right)^2 = \beta_{zi}^2 + \kappa_i^2} \qquad \textbf{[4.18]}$$

- β_1 is the propagation constant of a wave at frequency w in a medium of refractive index n_1 and κ_i is the eigen value or propagation constant in the transverse direction of propagation mode i.

z - Direction Propagation constant

- Since each propagation mode has a real κ_i, β_{zi} satisfies the following inequality
- $\beta_i^2 - \beta_{zi}^2 = \kappa_i^2 > 0$ ……………….4.19
- The higher the the propagation mode ψ_i or the larger the index i, the larger the κ_i and the smaller the β_{zi}. When κ_i exceeds β_i, β_{zi} becomes imaginary and the mode has an exponential decay as it propagates

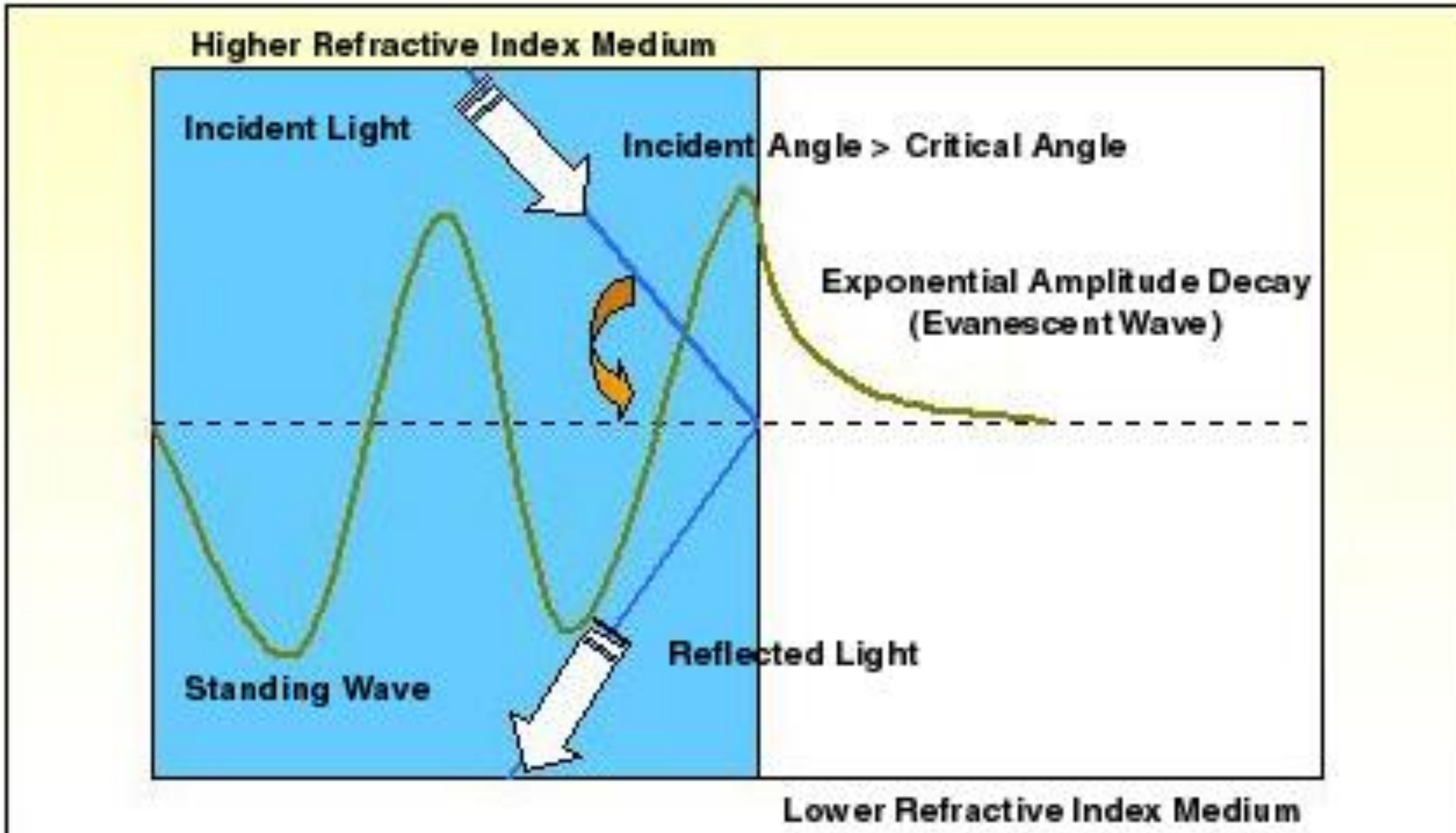
z - Direction Propagation constant

- Equation 4.19 is the propagation condition for the waves inside the core. There is a similar but different condition for them in the cladding:

$$\beta_{zi}^2 - \beta_2^2 > 0 \qquad [4.20]$$

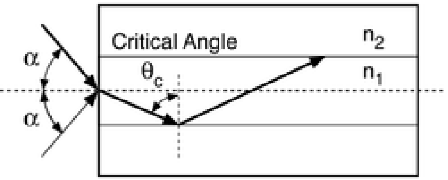
Where $\beta_2 = n_2\omega/c.$

- This condition requires no radial propagation in the cladding; in other words we have an evanescent wave



Evanescent Wave Generation

Numerical Aperture



$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$ Eq. 4.12

Full Acceptance Angle = 2α

z - Direction Propagation constant

- Equations 4.19 and 4.20 together require β_{zi} in the following range:

$$\boxed{\frac{n_2}{n_1} < \frac{\beta_{zi}}{\beta_1} < 1.} \qquad \textbf{[4.21]}$$

- This condition is the wave analysis counterpart of equation 4.10 from geometric optics
- Equation 4.12 shows that the closer n_2 is to n_1, the smaller the NA and the more difficult it is to inject a propagatable ray.
- Similarly equation 4.21 shows that the smaller the NA, the smaller the allowable range of β_{zi} . As a result there are fewer propagation modes

$$\theta_1 > \sin^{-1}\left(\frac{n_2}{n_1}\right) \stackrel{\text{def}}{=} \theta_{crit}. \qquad \textbf{[4.10]}$$

z – direction propagation velocity

- The z-direction velocity v_{gi} of the propagation mode i is a function of its propagation constant β_{zi} . v_{gi} is given by:

$$v_{gi} = \frac{\partial \omega}{\partial \beta_{zi}} \qquad \textbf{[4.22]}$$

- Which is known as the group velocity and tells us how fast the power of a light signal travels.
- This is different from the phase velocity, $v_{pi} = w / \beta_{zi}$, which tells us how fast the phase of the light signal changes

z – direction propagation velocity

Although the exact computation of the group velocity v_{gi} requires the knowledge of β_{zi} as a function of ω Equation (4.19) can be used to find an approximation when the frequency dependence of κ_i is small. In this case,

$$\beta_i^2 - \beta_{zi}^2 = \kappa_i^2 > 0 \qquad .4.19$$

$$\frac{\partial \beta_{zi}}{\partial \beta_1} \approx \frac{\beta_1}{\beta_{zi}}.$$

because $\beta_1 = n_1\omega/c$

$$\frac{\partial \beta_1}{\partial \omega} = \frac{1}{c}\frac{\partial(n_1\omega)}{\partial \omega} = \frac{1}{c}\left(n_1 + \omega\frac{\partial n_1}{\partial \omega}\right) \stackrel{\text{def}}{=} \frac{n_{1g}}{c} \stackrel{\text{def}}{=} \frac{1}{v_g} \qquad \textbf{[4.23]}$$

where

$$\boxed{n_{1g} = n_1 + \omega\frac{\partial n_1}{\partial \omega}} \qquad \textbf{[4.24]}$$

is called the **group refractive index.** From the above results, using the chain rule, we have

$$\boxed{v_{gi} = \frac{\partial \omega}{\partial \beta_{zi}} = \left(\frac{\partial \beta_{zi}}{\partial \omega}\right)^{-1} = \left(\frac{\partial \beta_{zi}}{\partial \beta_1}\frac{\partial \beta_1}{\partial \omega}\right)^{-1} \approx \left(\frac{\beta_1}{\beta_{zi}}\frac{n_{1g}}{c}\right)^{-1} = \frac{c}{n_{1g}}\frac{\beta_{zi}}{\beta_1} = v_g\frac{\beta_{zi}}{\beta_1}.} \qquad \textbf{[4.25]}$$

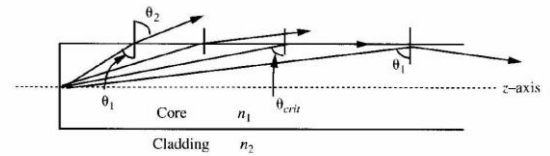


Figure 4.9 Light propagation using geometrical optics.

z – direction propagation velocity

- Comparing equation 4.25 with 4.11 shows the ratio of β_{zi} to β_1, is equivalent to $\sin(\theta_1)$ or the ratio of v_z to c/n_1 in figure 4.9.
- Because each propagation mode has its β_{zi}, each mode has a different propagation delay

$$\boxed{v_{gi} = \frac{\partial \omega}{\partial \beta_{zi}} = \left(\frac{\partial \beta_{zi}}{\partial \omega}\right)^{-1} = \left(\frac{\partial \beta_{zi}}{\partial \beta_1}\frac{\partial \beta_1}{\partial \omega}\right)^{-1} \approx \left(\frac{\beta_1}{\beta_{zi}}\frac{n_{1g}}{c}\right)^{-1} = \frac{c}{n_{1g}}\frac{\beta_{zi}}{\beta_1} = v_g \frac{\beta_{zi}}{\beta_1}.} \quad [4.25]$$

$$v_z = \frac{c}{n_1}\sin(\theta_1). \quad [4.11]$$

Geometric optics

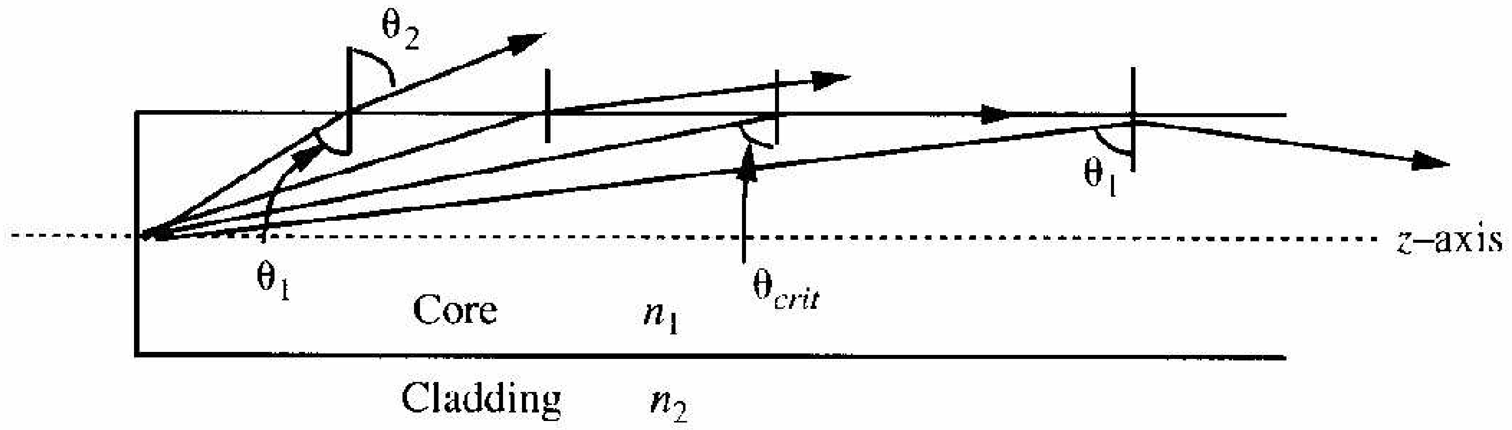


Figure 4.9 Light propagation using geometrical optics.

Fibre Dispersion

- In general there are three kinds of dispersion
  - Material or chromatic
  - Waveguide
  - Modal
- The first two types of dispersion are attributable to the frequency dependence of the propagation velocities and their summation is referred to as **intramodal** dispersion or group velocity dispersion
- The third type, called **intermodal** dispersion is due to the dependence of the propagation velocities on different propagation modes
- Single mode fibres only have **intramodal** dispersion

Intramodal Dispersion

- Because the group velocity of a given propagation mode is frequency dependent, the unit propagation delay (ie the inverse of the group velocity) is also frequency dependent.
- The taylor series expansion can be used to express the unit delay at a given wavelength λ as:

$$\tau_g = \tau_g(\lambda_0) + (\lambda - \lambda_0)\frac{\partial \tau_g}{\partial \lambda} + 0.5(\lambda - \lambda_0)^2\frac{\partial^2 \tau_g}{\partial \lambda^2} + \ldots \qquad \textbf{[4.26]}$$

where $\tau_g(\lambda_0)$ is the unit distance propagation delay at the central wavelength λ_0. From the expansion, the intramodal dispersion is defined by

$$D_{intra} \stackrel{\text{def}}{=} \frac{\partial \tau_g}{\partial \lambda} = \frac{\partial}{\partial \lambda}\left(\frac{1}{v_g}\right) = \frac{\partial}{\partial \lambda}\left(\frac{\partial \beta_z}{\partial \omega}\right) \qquad \textbf{[4.27]}$$

where the index i to β_{zi} is dropped for simplicity. Equation (4.26) thus reduces to

$$\boxed{\tau_g \approx \tau_g(\lambda_0) + (\lambda - \lambda_0)D_{intra} + 0.5(\lambda - \lambda_0)^2\frac{\partial D_{intra}}{\partial \lambda}.} \qquad \textbf{[4.28]}$$

Intramodal Dispersion

If we keep only the first two terms, the pulse width increase due to intramodal dispersion D_{intra} is given by

$$\boxed{\Delta\tau_g = D_{intra}\Delta\lambda} \qquad \textbf{[4.29]}$$

where $\Delta\lambda$ is the linewidth of the light signal.

To find $D_{intra,}$ using the definition given in Equation (4.27) and the chain rule gives

$$D_{intra} = \frac{\partial}{\partial\lambda}\left(\frac{\partial\beta_z}{\partial\beta_1}\frac{\partial\beta_1}{\partial\omega}\right).$$

From Equation (4.23), D_{intra} reduces to

$$\boxed{D_{intra} = \frac{1}{c}\frac{\partial n_{1g}}{\partial\lambda}\frac{\partial\beta_z}{\partial\beta_1} + \frac{n_{1g}}{c}\frac{\partial}{\partial\lambda}\left\{\frac{\partial\beta_z}{\partial\beta_1}\right\} \stackrel{\text{def}}{=} D_{material} + D_{waveguide}} \qquad \textbf{[4.30]}$$

$$\frac{\partial\beta_1}{\partial\omega} = \frac{1}{c}\frac{\partial(n_1\omega)}{\partial\omega} = \frac{1}{c}\left(n_1 + \omega\frac{\partial n_1}{\partial\omega}\right) \stackrel{\text{def}}{=} \frac{n_{1g}}{c} \stackrel{\text{def}}{=} \frac{1}{v_g} \qquad \textbf{[4.23]}$$

Intramodal Dispersion

where

$$\boxed{D_{material} \stackrel{\text{def}}{=} \frac{1}{c}\frac{\partial n_{1g}}{\partial \lambda}\frac{\partial \beta_z}{\partial \beta_1} \approx \frac{1}{c}\left(-\lambda\frac{\partial^2 n_1}{\partial \lambda^2}\right)\frac{\beta_1}{\beta_z} \approx \frac{1}{c}\left(-\lambda\frac{\partial^2 n_1}{\partial \lambda^2}\right)} \qquad [4.31]$$

is the material dispersion, and

$$\boxed{D_{waveguide} \stackrel{\text{def}}{=} \frac{n_{1g}}{c}\frac{\partial}{\partial \lambda}\left(\frac{\partial \beta_z}{\partial \beta_1}\right)} \qquad [4.32$$

Is the waveguide dispersion

Intramodal Dispersion

- $D_{material}$ is independent of the propagation mode and solely depends on the frequency dependence of the refractive index n_1 . $D_{material}$ of typical silica optical fibres as a function of wavelength is shown in figure 4.12
- $D_{waveguide}$ on the other hand, depends on the propagation mode i, which in turn is determined by the optical waveguide structure

Intramodal Dispersion

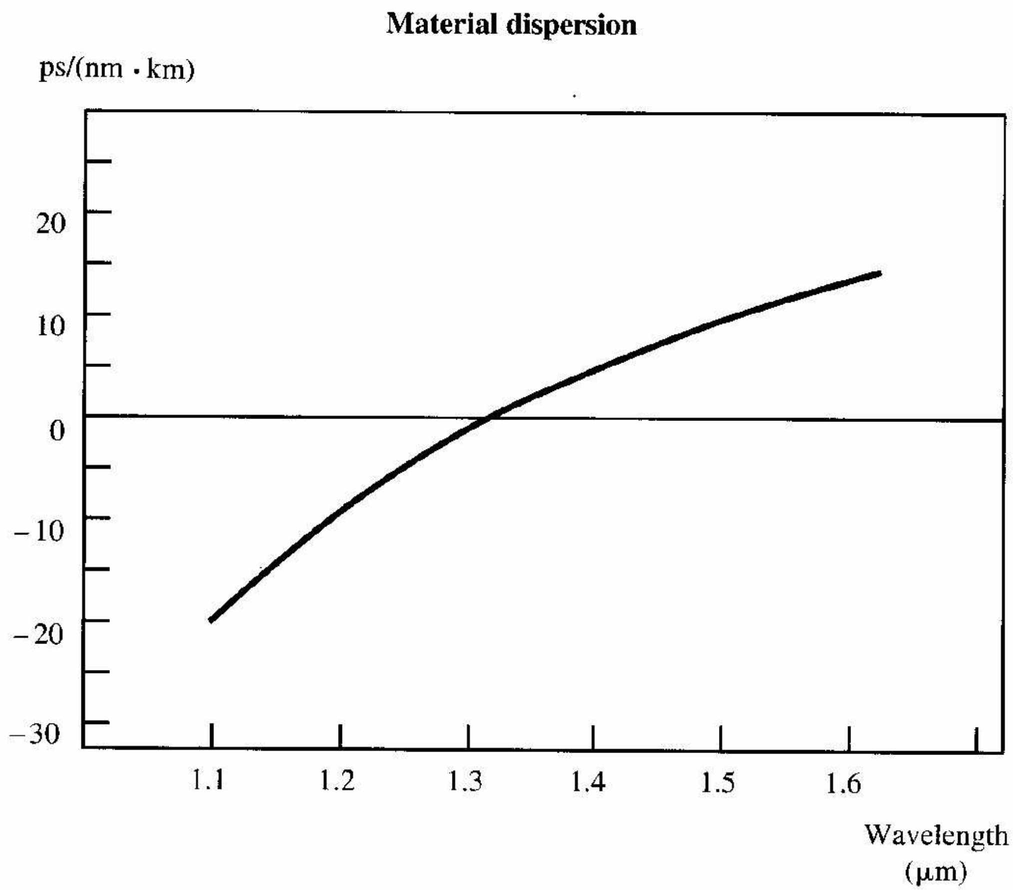


Figure 4.12 Material dispersion in optical fibers.

Intermodal dispersion

- Caused by different propagation delays of different propagation modes
- This can be seen from equation 4.19, where β_{zi} is different for different propagation modes. Therefore, the corresponding group velocity v_{gi} in equation 4.22 is also different. Specifically modal dispersion can be defined as:

$$D_{modal} = \frac{1}{v_{g,min}} - \frac{1}{v_{g,max}} = \tau_{g,max} - \tau_{g,min} \qquad \textbf{[4.33]}$$

- Where $\tau_{g,max}$ *and* $\tau_{g,min}$ are the maximum and minimum unit group propagation delays, respectively

Intermodal dispersion – step-index

- One can estimate the modal dispersion of step index fibres from geometric optics. Substituting the two limiting cases $\theta_1 = \theta_{crit}$ and 90^0 into equation 4.11 gives:

$$v_z = \frac{c}{n_1}\sin(\theta_1). \qquad [4.11]$$

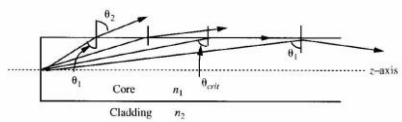


Figure 4.9 Light propagation using geometrical optics.

$$\tau_{g,max} \approx \frac{n_{1g}}{c}\frac{1}{\sin(\theta_{crit})} = \frac{n_{1g}}{c}\frac{n_1}{n_2} \qquad [4.34]$$

and

$$\tau_{g,min} \approx \frac{n_{1g}}{c}. \qquad [4.35]$$

The modal dispersion is thus

$$\boxed{D_{modal} = \tau_{g,max} - \tau_{g,min} \approx \frac{n_{1g}}{c}\left(\frac{n_1}{n_2} - 1\right) = \frac{n_{1g}}{c}\Delta.} \qquad [4.36]$$

- This simple result shows that the intermodal dispersion in step-index fibres is proportional to the refractive index difference
- Because NA is proportional to $\Delta^{1/2}$, there is a trade off between the coupling efficiency and dispersion.

$$\Delta \stackrel{\text{def}}{=} \frac{n_1 - n_2}{n_2} \approx \frac{n_1 - n_2}{n_1}$$

Intermodal dispersion – graded-index

- The refractive index profile of graded-index fibres can generally be expressed as:

$$n(r) = \begin{cases} n_1(1 - 2\Delta[(r/a)]^\alpha)^{1/2} & \text{for } r < a \\ n_1(1 - 2\Delta)^{1/2} = n_2 & \text{for } r \geq a \end{cases} \qquad \textbf{[4.37]}$$

- Where α is a parameter that can be optimised for minimal modal dispersion

When $\alpha = 2(1 - \Delta)$ **[4.38]**

the modal dispersion is minimized and given by

$$\boxed{D_{modal} = \frac{n_{1g}}{c}\frac{\Delta^2}{8}.} \qquad \textbf{[4.39]}$$

Intermodal dispersion – graded-index

- Thus the modal dispersion for graded-index fibres is much smaller than that of step-index fibres, given by equation 4.36, because of the Δ^2 factor.
- It has also been shown that the longitudinal propagation constant $\beta_{z,m}$ of each propagation mode can be approximated by:

$$\beta_{z,m} \approx \beta_1 \left[1 - 2\Delta\left(\frac{m}{M}\right)^g\right]^{1/2} \quad \textbf{[4.40]}$$

where $g = \alpha/(\alpha + 2)$ and

$$M \approx a^2\beta_1^2\left(\frac{\alpha\Delta}{\alpha + 2}\right) \quad \textbf{[4.41]}$$

is the total number of propagation modes.

Total fibre dispersion

- From the intramodal and intermodal dispersions, one can obtain the total dispersion. Instead of adding them directly, it is given by the following square sum expression:

$$\boxed{D_{total}^2 = D_{intra}^2 \Delta\lambda^2 + D_{modal}^2} \qquad [4.42]$$

- Where $\Delta\lambda$ is the linewidth in nm of the light spectrum
- Because the fibre is a communication channel, the total fibre dispersion is often used to characterise the fibre's transmission bandwidth.
- Because the total propagation delay difference is proportional to $D_{total}L$, the fibre bandwidth is defined as:

$$\boxed{B_{fiber} \stackrel{\text{def}}{=} \frac{1}{D_{total}L}.} \qquad [4.43]$$

- Hence, the larger the total dispersion and the longer the distance, the lower the transmittable bit rate

Modal Dispersion at Longer Distance

- In general the dispersion is linearly proportional to L, the total transmission distance
- When modal dispersion dominates and the fibre is longer than a critical length the total dispersion is proportional to the square root of L.
- This dependence on L is shown in figure 4.13. This is due to mode coupling

Modal Dispersion at Longer Distance

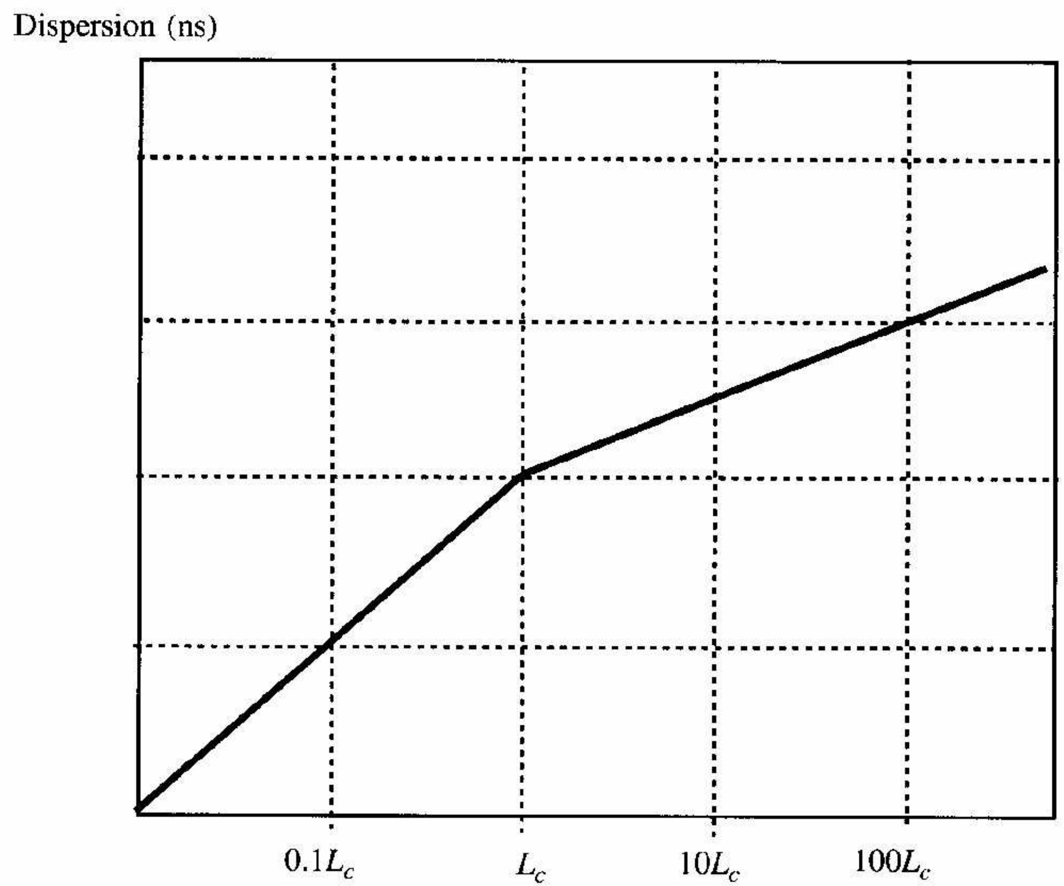


Figure 4.13 The reduction in modal dispersion due to mode coupling.

Dispersion Limits

- Dispersion places an upper bound for the maximum transmission distance at a given bit rate, this is called the dispersion limit.
- When binary bits of 1's and 0's are transmitted, as illustrated in figure 4.14, they are transmitted as a series of optical pulses
- Assume each pulse has a width T_0 equal to the bit period.
- When pulses arrive at the other end of the fibre, they become broader because of fibre dispersion

Dispersion Limits

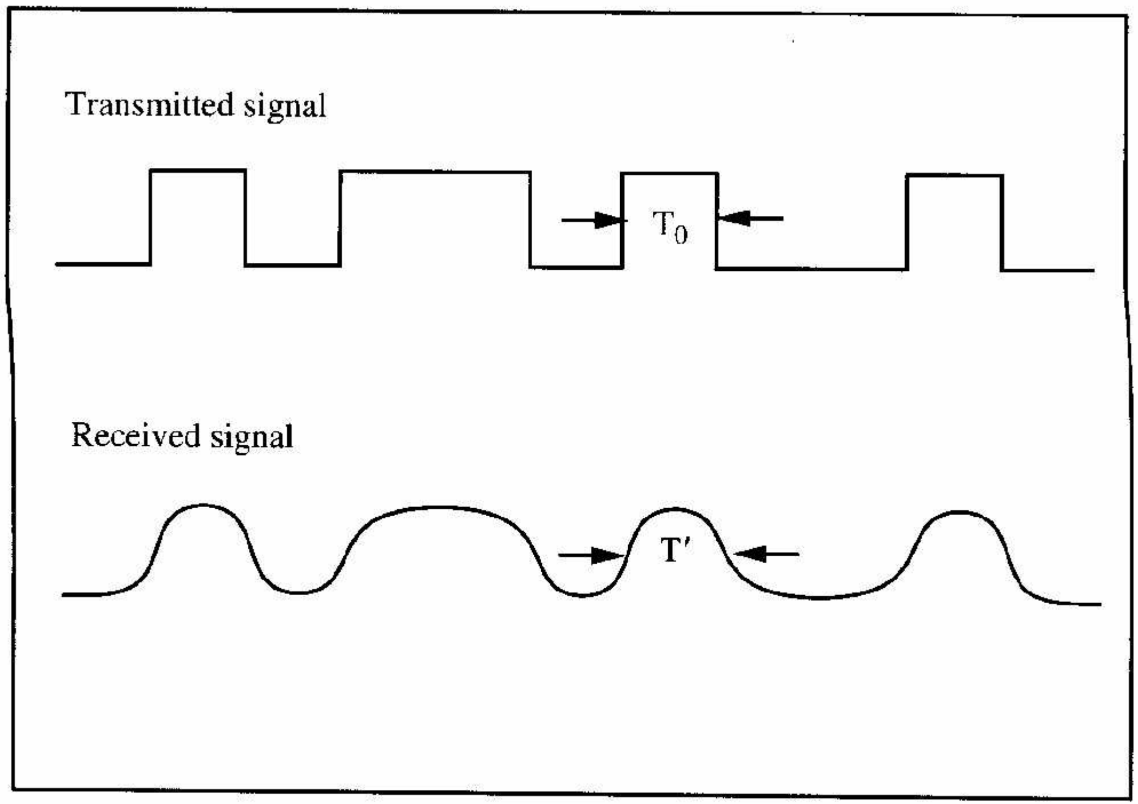


Figure 4.14 Transmitted and received optical pulses.

Dispersion Limits

- Assume that the received pulse has a width T' with $T' > T_0$, this results in pulse overlap
- This interference is called intersymbol interference and results in an increase of the BER
- In general the BER will not be increased until $\Delta T' = T' - T_0$ becomes too large. A rule of thumb is that if

$$\boxed{\Delta T = T' - T_0 = D_{total} L \leq \frac{T_0}{4} = \frac{1}{4B}} \qquad [4.44]$$

- The BER will not be degraded significantly

Dispersion Limits

- Other factors such as the rise time of the light source and receiver can also contribute to pulse broadening
- The total pulse broadening is a square sum of all these factors. Therefore:

$$\Delta T^2 = \tau_t^2 + \tau_r^2 + (D_{total} L)^2 \qquad \textbf{[4.45]}$$

Where τ_t, and τ_r, are the rise times of the transmitter and receiver, respectively. Combining equations (4.44) and (4.45) gives

$$\boxed{\tau_t^2 + \tau_r^2 + (D_{total} L)^2 < \left(\frac{1}{4B}\right)^2 .} \qquad \textbf{[4.46]}$$

- This is the general expression for the dispersion limit

Dispersion dependent on bit rate

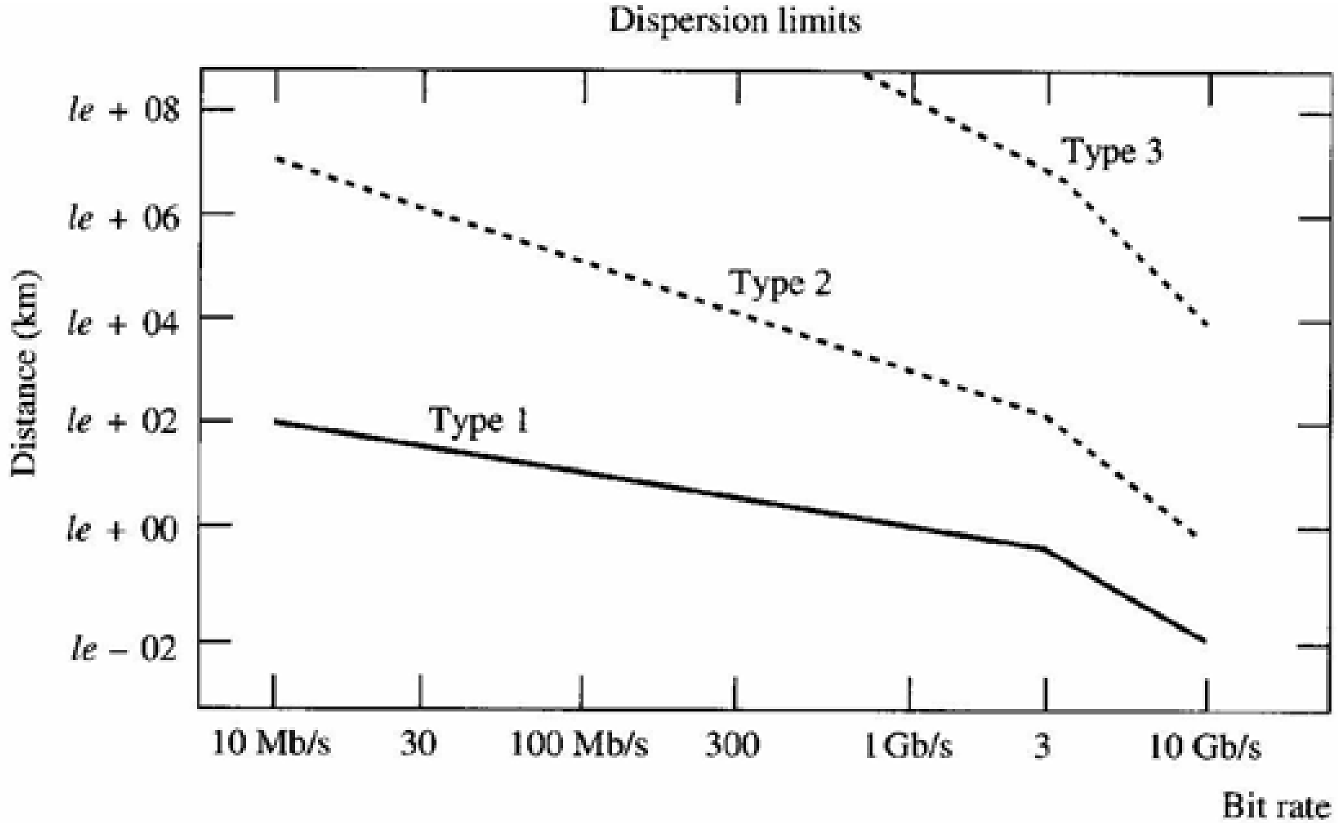


Figure 4.15 The three types of dispersion limits. Type 1 is independent of bit rate, type 2 is proportional to bit rate, and type 3 is proportional to bit rate squared.

Fibre dispersion independent of bit rate

- From equation 4.42, dispersion ΔT can be independent of B when either intermodal dispersion dominates or when $\Delta\lambda$ does not depend on B
- For example, in step-index multimode fibres, the modal dispersion is much larger than the intramodal dispersion
- In single mode or graded-index multimode fibres, if the light source used is an LED or a multimode FP laser diode where the linewidth of the source is much greater than B, $\Delta\lambda$ will be independent of B

$$\boxed{D_{total}^2 = D_{intra}^2 \Delta\lambda^2 + D_{modal}^2} \qquad [4.42]$$

Fibre dispersion independent of bit rate

In either case, Equation (4.46) gives

$$\boxed{D_{total} L < \left[\left(\frac{1}{4B} \right)^2 - \tau_t^2 - \tau_r^2 \right]^{1/2}.} \qquad [4.47]$$

For convenience, let

$$B_{max} \stackrel{\text{def}}{=} \frac{1}{4(\tau_t^2 + \tau_r^2)^{1/2}} \qquad [4.48]$$

be the maximum achievable bit rate. Then,

$$\boxed{L < L_{max} = \frac{1}{4 D_{total}} \left(\frac{1}{B^2} - \frac{1}{B_{max}^2} \right)^{1/2}.} \qquad [4.49]$$

Note that D_{total} has the dimension sec/km.

Fibre dispersion proportional to bit rate

- When single mode fibres are used, there is no intermodal dispersion
- If a single mode light source and external modulation are used, the output linewidth $\Delta\lambda$ will be of the order of B
- For AM modulation the spectrum width under external modulation can be as low as 2B (lower band plus upper band)
- Depending on the modulation scheme, the spectrum width of the modulated light signal takes the form:

$$\tau_t^2 + \tau_r^2 + (D_{total} L)^2 < \left(\frac{1}{4B}\right)^2. \qquad \textbf{[4.46]}$$

Fibre dispersion proportional to bit rate

$$\Delta f = k_b B$$

where $k_b = 2$ for AM modulation. Since the linewidth $\Delta\lambda$ is related to the spectrum width by $\Delta\lambda = (\lambda^2/c)\Delta f$ (see Equation [3.4]), we have

$$D_{total} = D_{intra} \times \Delta\lambda = D_{intra} \times (k_b B)\frac{\lambda^2}{c}. \qquad \textbf{[4.50]}$$

Combining Equations (4.46) and (4.50) gives

$$\boxed{L \le \frac{c}{4k_b\lambda^2}\frac{1}{D_{intra}}\frac{1}{B}\left(\frac{1}{B^2} - \frac{1}{B_{max}^2}\right)^{1/2}.} \qquad \textbf{[4.51]}$$

When $B \ll B_{max}$, L is inversely proportional to B^2.

Fibre dispersion proportional to bit rate squared

- In addition to using single mode fibres, single mode light sources and external modulation, one can further improve the dispersion limit, if the lightwave is at either 1300 nm, or 1550nm, using dispersion shifted fibres
- In this case, D_{intra} = 0 and the second order term in equation 4.26 must be included. Thus:

$$\tau_g = \tau_g(\lambda_0) + (\lambda - \lambda_0)\frac{\partial \tau_g}{\partial \lambda} + 0.5(\lambda - \lambda_0)^2 \frac{\partial^2 \tau_g}{\partial \lambda^2} + \ldots \qquad \textbf{[4.26]}$$

$\tau_g(\lambda_0)$ is the unit distance propagation delay at the central wavelength λ_0. From the pansion, the intramodal dispersion is defined by

$$D_{intra} \stackrel{\text{def}}{=} \frac{\partial \tau_g}{\partial \lambda} = \frac{\partial}{\partial \lambda}\left(\frac{1}{v_g}\right) = \frac{\partial}{\partial \lambda}\left(\frac{\partial \beta_z}{\partial \omega}\right) \qquad \textbf{[4.27]}$$

here the index i to β_{zi} is dropped for simplicity. Equation (4.26) thus reduces to

$$\boxed{\tau_g \approx \tau_g(\lambda_0) + (\lambda - \lambda_0) D_{intra} + 0.5(\lambda - \lambda_0)^2 \frac{\partial D_{intra}}{\partial \lambda}.} \qquad \textbf{[4.28]}$$

Fibre dispersion proportional to bit rate squared

$$\Delta\tau_g \approx \frac{1}{2}\frac{\partial D_{intra}}{\partial\lambda}(\lambda-\lambda_0)^2 \qquad 4.52$$

where λ_0 is the wavelength at which $\frac{\partial D_{intra}}{\partial\lambda} = 0$. If λ_0 is also at the center of the linewidth $\Delta\lambda$, the maximum deviation of $|\,\lambda = \lambda_0\,|$ is

$$\max|\lambda-\lambda_0| = \frac{\Delta\lambda}{2} = \frac{\lambda^2 k_b}{2c}B.$$

Therefore, the fiber dispersion is

$$\Delta\tau_g \approx \frac{1}{2}\frac{\partial D_{intra}}{\partial\lambda}\left(\frac{\lambda^2 k_b}{2c}B\right)^2 \qquad 4.53$$

and the dispersion limit is

$$L < \frac{1}{2dD_{intra}/d\lambda}\left(\frac{2c}{\lambda^2 k_b}\right)^2 \frac{1}{B^2}\left(\frac{1}{B^2}-\frac{1}{B_{max}^2}\right)^{1/2}. \qquad 4.54$$

Dispersion dependent on bit rate

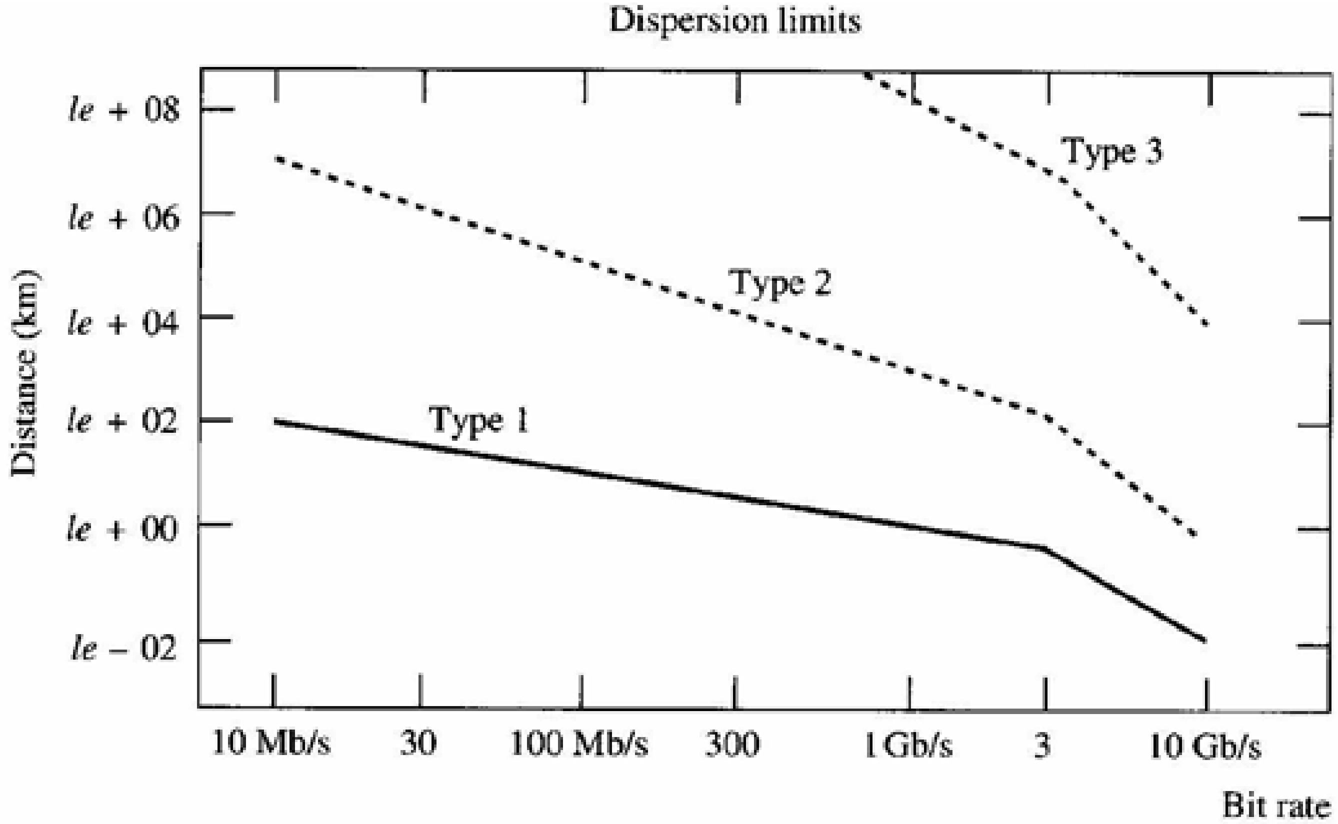
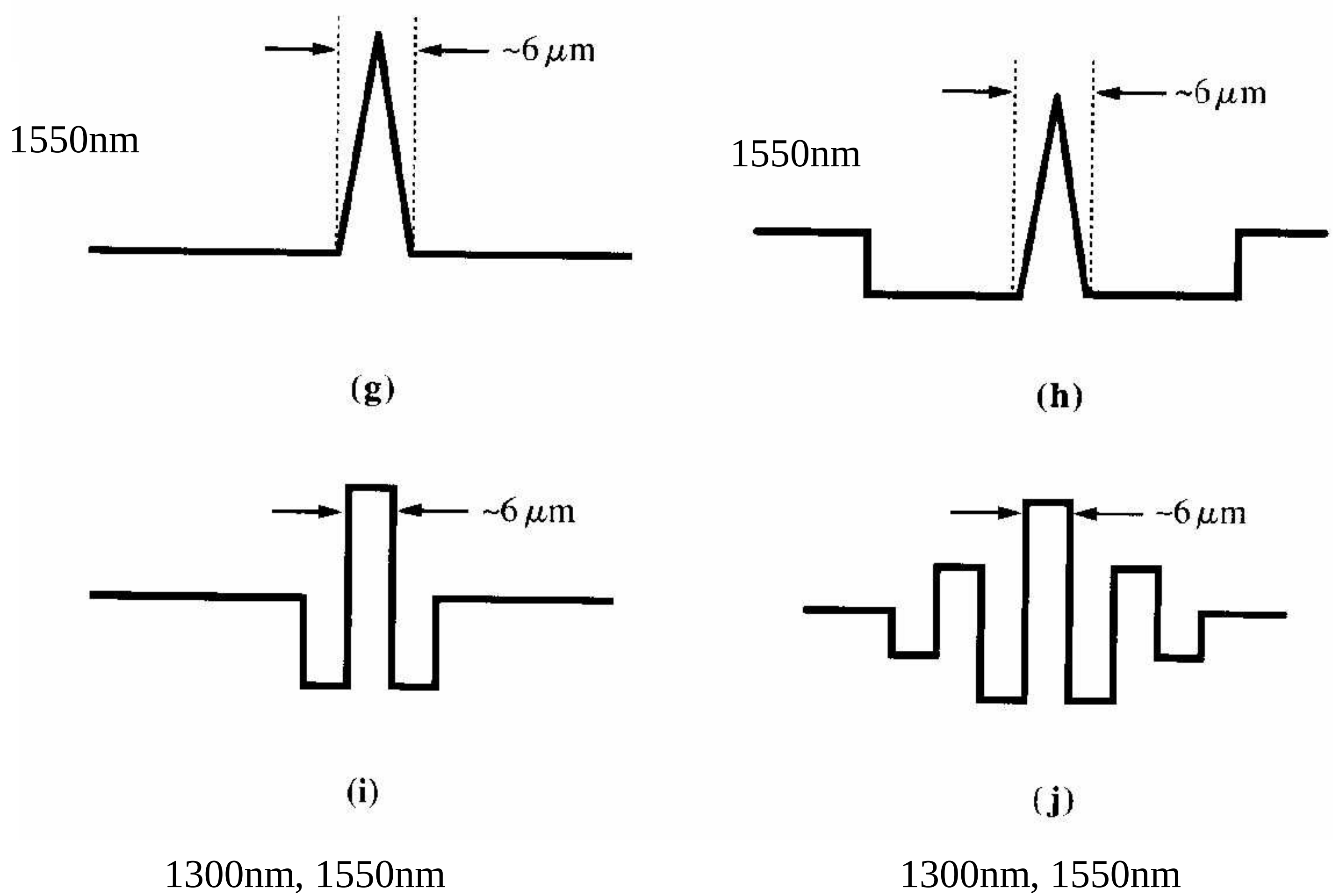


Figure 4.15 The three types of dispersion limits. Type 1 is independent of bit rate, type 2 is proportional to bit rate, and type 3 is proportional to bit rate squared.

Dispersion shifted and multiply clad fibres

- **Dispersion-shifted fibres minimize dispersion at one point: 1550 nm, where the fibre attenuation is at its minimum**
- **Multiply clad fibres are designed to minimise fibre dispersion over a wide wavelength range**
- **Because D_{intra} is the sum of $D_{material}$ and $D_{waveguide}$, as illustrated in figure 4.17, D_{intra} can be made zero by adjusting $D_{waveguide}$ in dispersion shifted fibres**
- **There are two methods to adjust $D_{waveguide}$**
- **First the refractive index of the fibre can be changed a shown in figure 4.3g and h, a triangular refractive index profile can be used for this purpose**

Figure 4.3 Refractive index profiles of *(a)* step-index multimode fibers, *(b)* graded-index multimode fibers, *(c)* match-cladding single-mode fibers, *(d)*–*(e)* depressed-cladding single-mode fibers, *(f)*–*(h)* dispersion-shifted fibers, and *(i)*–*(j)* dispersion-flattened fibers.



Dispersion shifted and multiply clad fibres

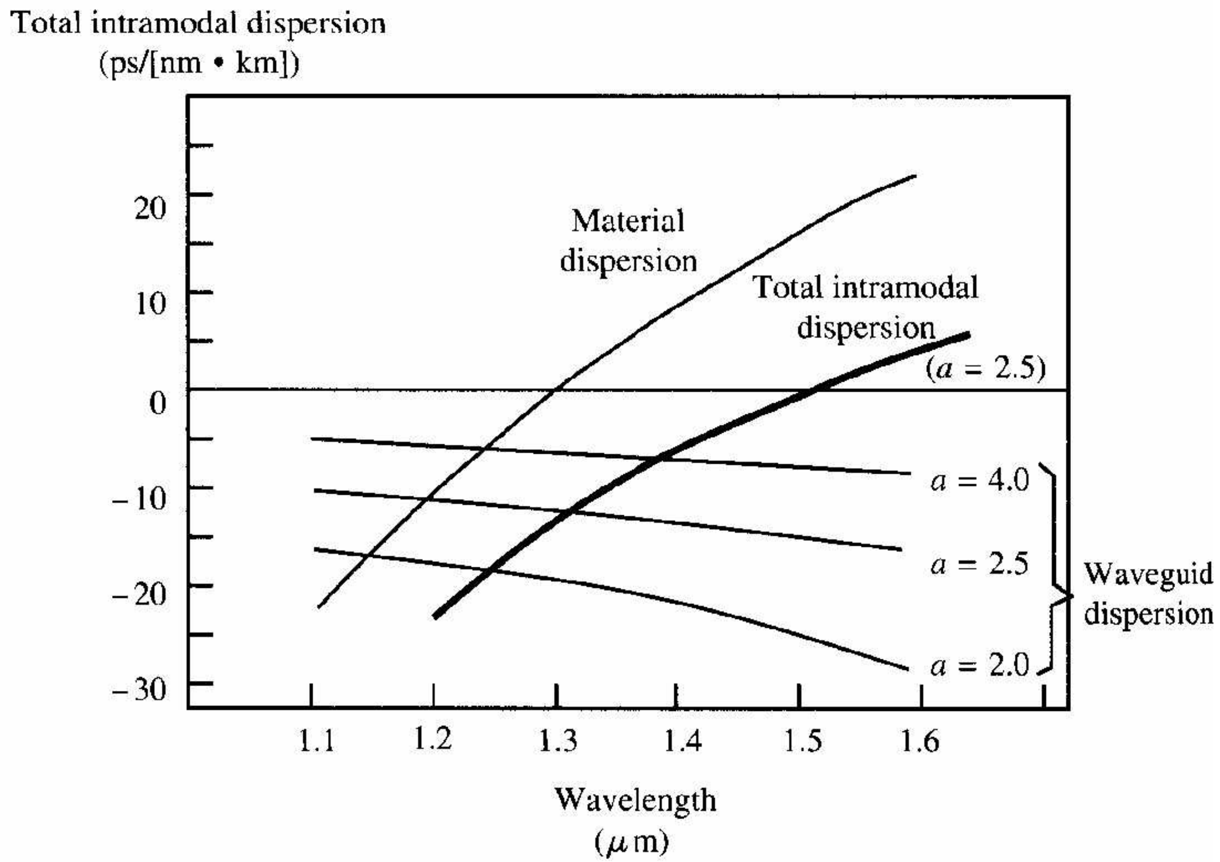


Figure 4.17 Total intramodal dispersion as a function of wavelength.

Dispersion shifted and multiply clad fibres

- Another way to adjust $D_{waveguide}$ is to change the core diameter. $D_{waveguide}$ is a function of the normalised frequency V defined by:

$$V \stackrel{\text{def}}{=} ka(n_1^2 - n_2^2)^{1/2} \approx \beta_1 a(2\Delta)^{1/2}. \quad \text{........4.55}$$

- Because V is proportional to k or f, V is commonly referred to as the normalised frequency, V and NA are similar quantities
- One can reduce $D_{waveguide}$ to zero by reducing V
- $D_{intra} = 0$ can be achieved at 1550 nm by reducing V through reducing the core radius 'a'

Multiply clad fibres

- For small dispersion over a wide wavelength range, multiply clad fibres can be used
- Doubly clad and quadruply clad fibre are illustrated in figure 4.3i and j
- Their low dispersion over a wide wavelength range is illustrated in figure 4.18
- These multiply clad fibres have two zero dispersion points

Multiply clad fibres

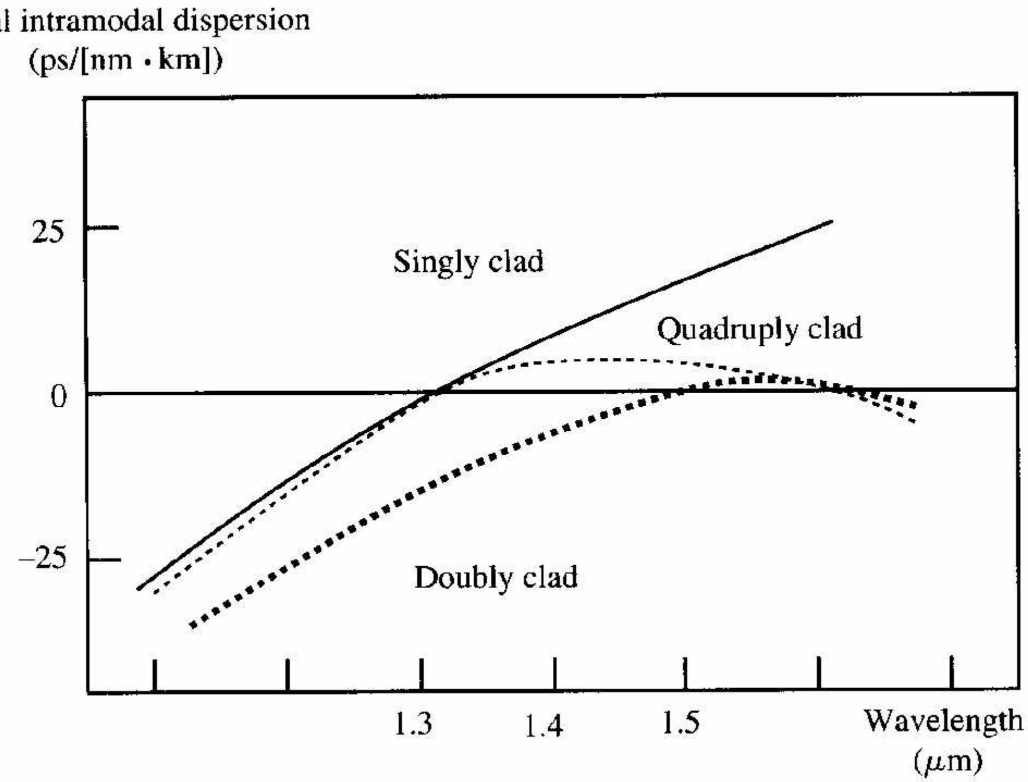
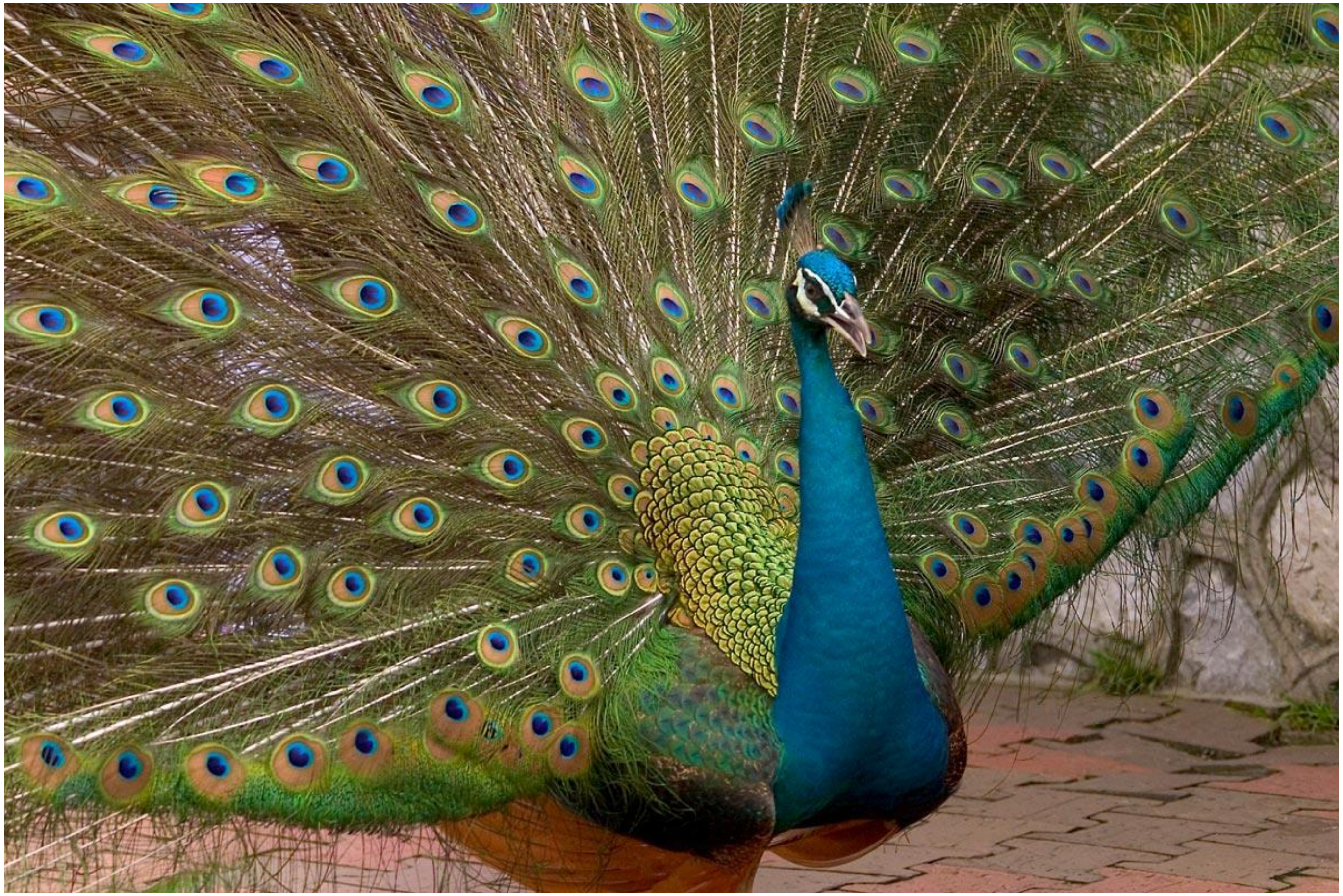


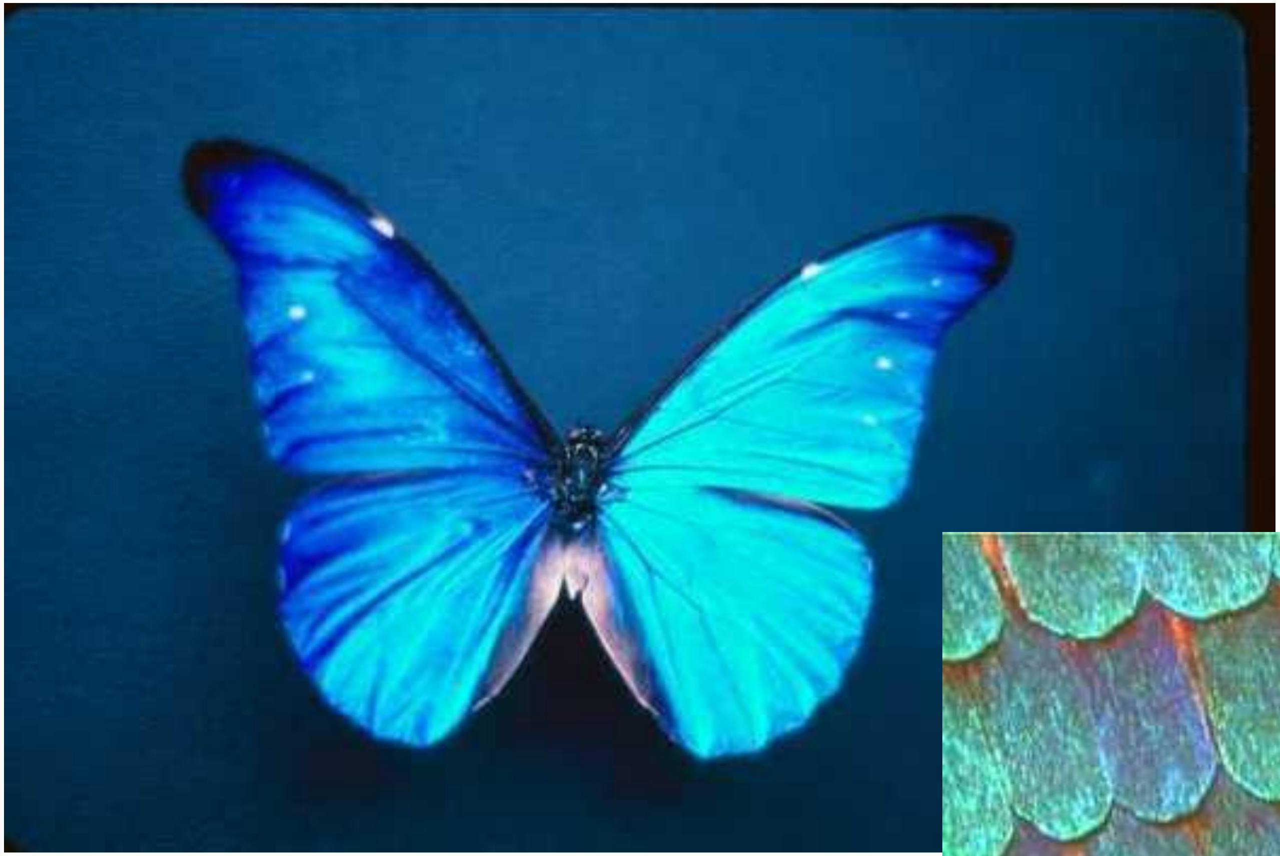
Figure 4.18 Dispersion characteristics of multiply clad fibers.

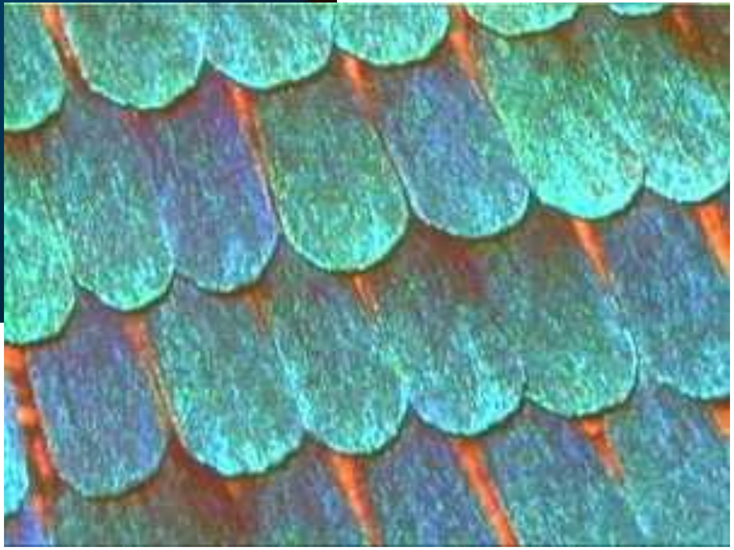
Photonic Crystals in Nature



The photonic crystal produces a bright iridescence that stands out. Peacocks also use photonic crystals in the spots on their tail feathers

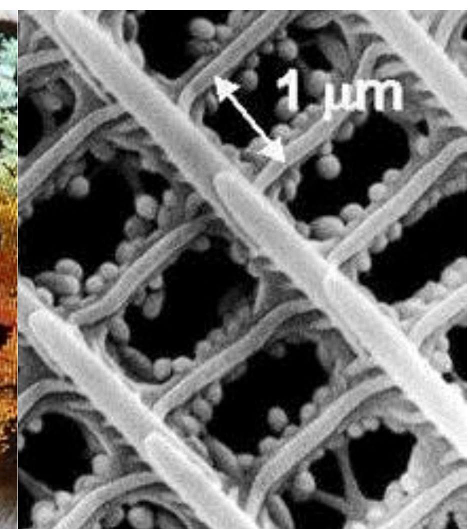
Photonic Crystals in Butterfly Wings



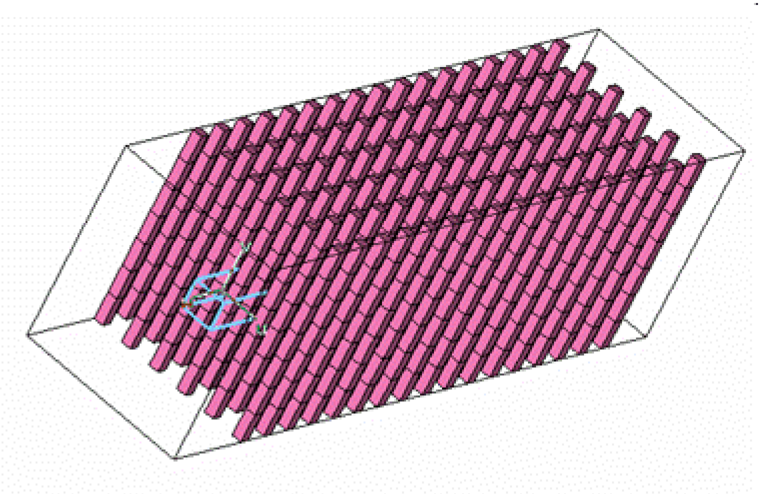


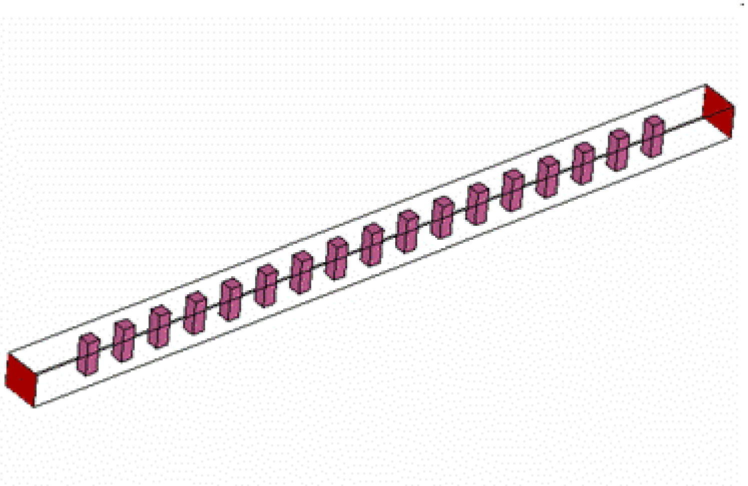
The periodic microstructure in the butterfly wing as well as in PBG fibers results in a so called photonic bandgab, where light in certain wavelength regions cannot propagate. In the butterfly wing this light is reflected back, and is seen as the bright colors.

Photonic Crystals in Butterfly Wings



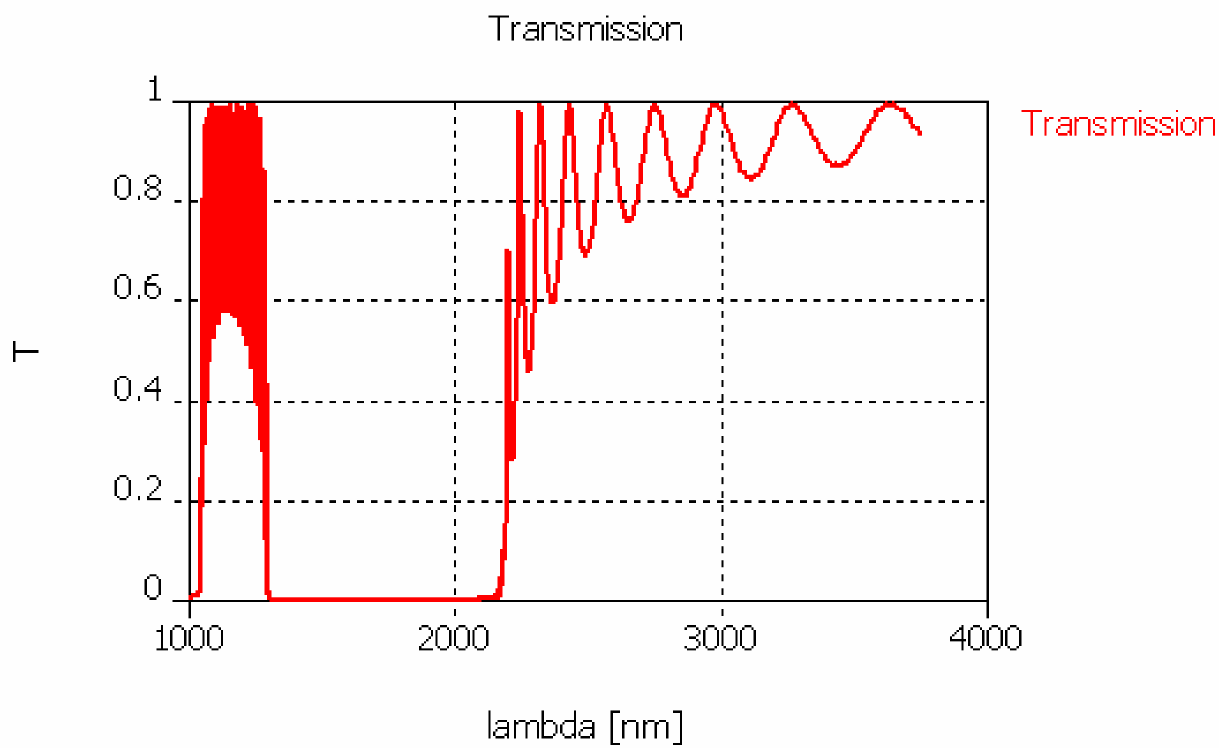
Photonic Crystals





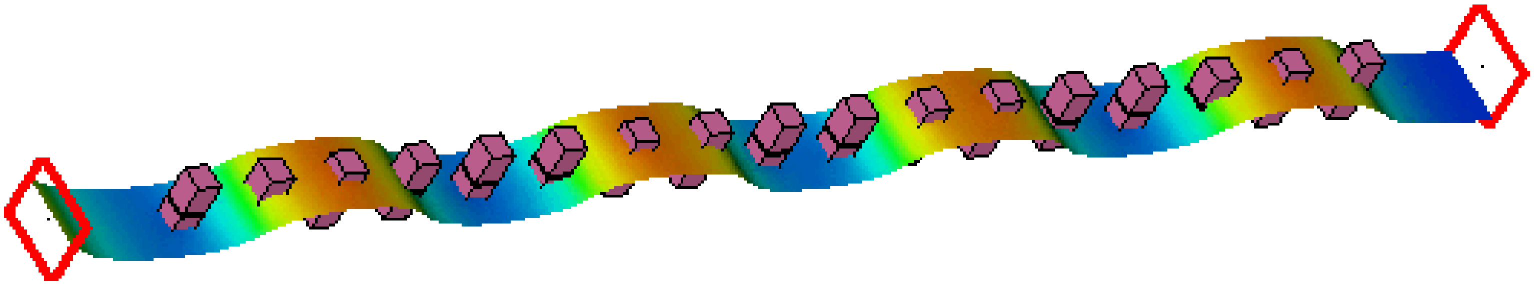
The rods are made from GaAS with refractive index of 3.4 and with an edge length of about 180 nm. The lattice spacing between the rods is 760 nm. As a first step, the transmission of a plane wave through this crystal is simulated.

Photonic Band Gap (PBG)



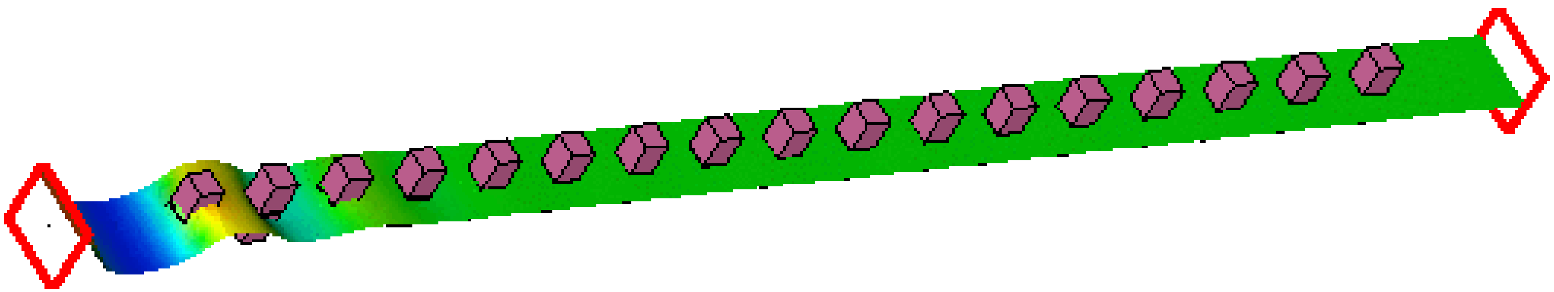
The transmission through the structure. Between 1400 and 2200 nm the transmission is zero. In this bandgap region no wave propagation is possible

Plane Wave Propagation through a PBG



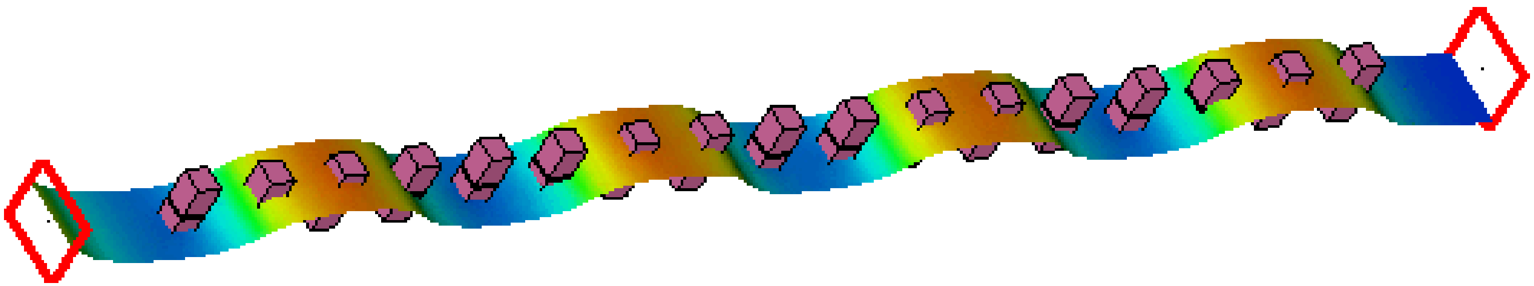
Wave Propagation at frequencies below the band gap

Plane Wave Propagation through a PBG



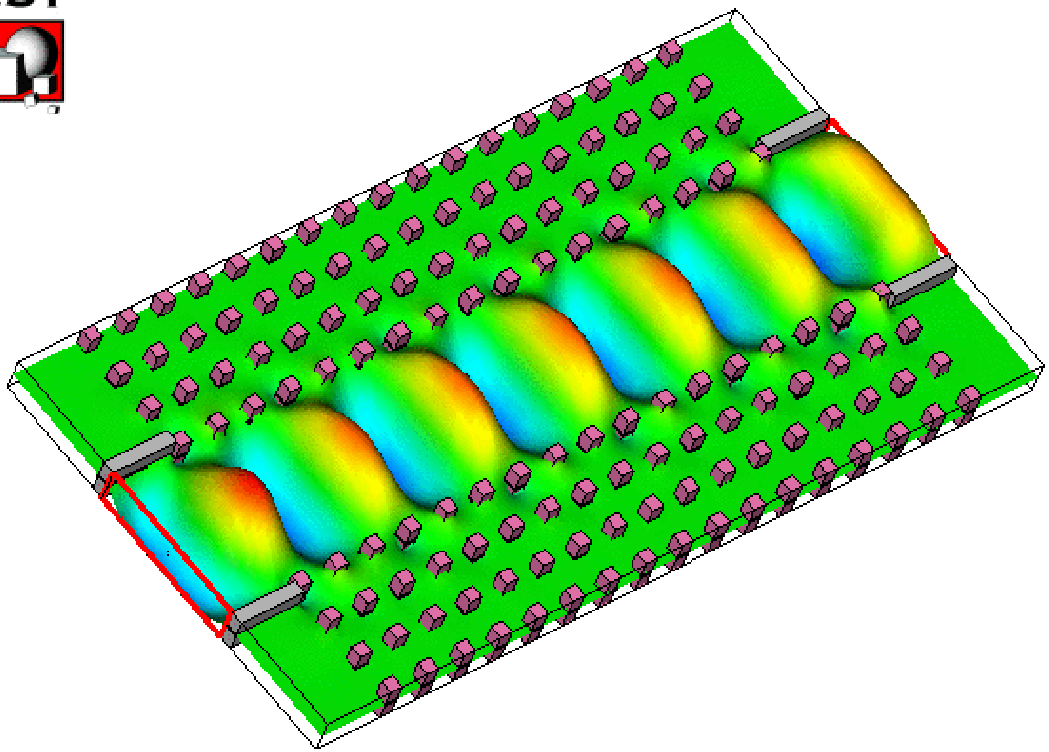
Wave propagation at frequencies in the band gap

Plane Wave Propagation through a PBG



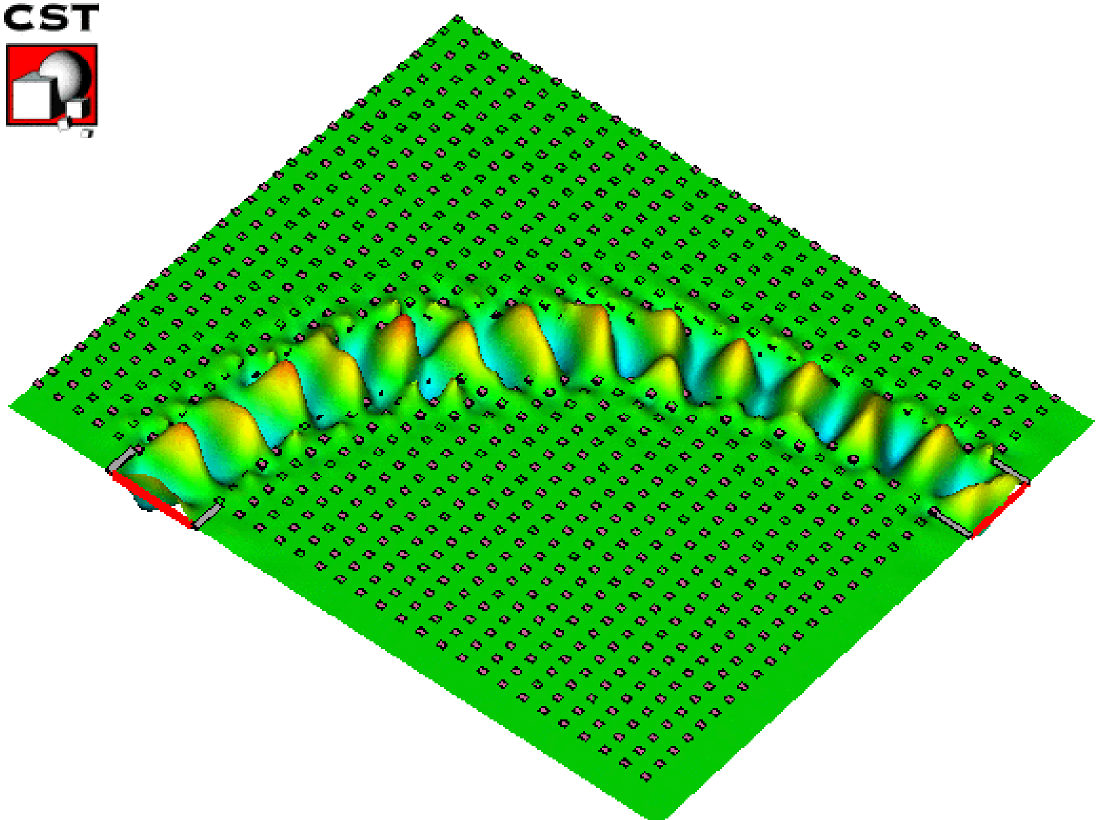
Wave Propagation at frequencies above the band gap

Waveguide



Shows the periodic PBG structure as described above. A line defect is introduced and the structure is excited with a electromagnetic wave at band gap frequencies. The wave can only propagate inside the line defect.

Waveguide



Wave propagation inside the Photonic crystal with a bent defect. Again, the structure is driven with a time harmonic signal. The signal frequency is inside band gap of the crystal. Consequently, the wave propagates inside bend defect

Integrated Photonics

- A single point defect in a Photonic Crystal leads to well-defined, localized states within the band gap.
- Suitably engineered defect states, therefore,comprise the smallest microresonators for the optical frequency range. In fact, lasing action based on point defects in Photonic Crystals has already been demonstrated.
- Chaining point defects together leads to the formation of a defect band within the photonic band gap
- Giving the possibility of realizing waveguiding structures of almost any shape on smallest length scales, thus paving the way to an integrated photonics.

The End